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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Broadband Radio Access Networks (BRAN).

1 Scope

The present document addresses the architecture, the economic model and the derivation of technical requirements for a BWA system, providing 1 Gbit/s/km^2, using 40 MHz of licensed spectrum and including self-backhauling in both licensed and un-licensed bands, network MIMO, cognitive-radio based self-organization, etc.

2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the reference document (including any amendments) applies.

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2.1 Normative references

The following referenced documents are necessary for the application of the present document.

Not applicable.

2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI TR 125 942 (2009): "Universal Mobile Telecommunications System (UMTS); Radio Frequency (RF) system scenarios (3GPP TR 25.942 version 9.0.0)".

[i.2] A. Papadogiannis and A. G. Burr: "Multi-beam Assisted MIMO - A Novel Approach to Fixed Beamforming", Future Network and Mobile Summit (FNMS 2011), Warsaw, Poland, June 2011.

[i.3] UMTS Forum: "Mobile Broadband Evolution: the roadmap from HSPA to LTE", Feb., 2009.

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[i.5] F. Akyildiz, et al.: "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey", Computer Networks, vol. 50, pp. 2127-2159, Sep, 2006.

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[i.9] Farahmand, A.-M.: "Interaction of culture-based learning and cooperative co-evolution and its application to automatic behavior-based system design", Evolutionary Computation, IEEE Transactions on, vol. 14, pp. 23 -57, Feb. 2010.

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[i.11] Mischa Dohler: "Docitive Radios - Centroid of Cognition and Cooperation", Keynote, WWRF23, October 2009, Beijing, China.

[i.12] Mischa Dohler: "Docitive Networks - A Step Beyond Cognition", Keynote, ISABEL 2009, November 2009, Bratislava, Slovakia.

[i.13] Mischa Dohler, L. Giupponi, A. Galindo-Serrano, P. Blasco: "Docitive Networks: A Novel Framework Beyond Cognition", IEEE Communications Society, Multimdia Communications TC, E-Letter, January 2010.

[i.14] ITU-R Recommendation P.530-12: "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems".

[i.15] P. Blasco, L. Giupponi, A. Galindo, M. Dohler: "Aggressive Joint Access & Backhaul Design For Distributed-Cognition 1Gbps/km2 System Architecture", in Proceedings of 8th International Conference on Wired/Wireless Internet Communications (WWIC 2010), 1-3 June, 2010, Lulea (Sweden).

[i.16] BuNGee deliverable D3.1: "Baseline RRM & Joint Access/Self-Backhaul Protocols".

3 Definitions and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

Adaptive Antenna System (AAS): system adaptively exploiting more than one antenna to improve the coverage and the system capacity

self-backhauling: wireless links between HBS and ABS, which may share a frequency channel with the access operation (in-band) and use in addition license-exempt spectrum, as 5 GHz or 60 GHz bands (out-of-band)

3.2 Abbreviations

For the purposes of the present document, the following abbreviations apply:

4G	4th Generation
AAA	Authentication, Authorization, and Accounting
ABS	Access BS
ACK	Acknowledge
ADC	Analogue To Digital Converter
AP	Access Point
ART	Above Roof Top
ASN	Access Service Network
BCC	BWA Control Channel
BER	Bit Error Rate
BF	Beam Forming
BM	Buttler Matrix
BRT	Below Roof Top
BS	Base Station
BS-BS	Base Station to Base Station
BW	Bandwidth
BWA user	Fixed, Nomadic or Mobile user
BWA	Broadband Wireless Access
CAPEX	Capital Expenditure
CAPEX	Capital Expenditure
CINR	Carrier to Interference and Noise Ratio
CQI	Channel Quality Indicator
CR	Cognitive Radio
CSI	Channel State Information
CTC	Clear Timer on Compare
DCO	Direct Communication Operation

DCS	Dynamic Channel Selection
DFS	Dynamic Frequency Selection
DL	Downlink
FBS	Femto BS
FCC	Forward Error Correction
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FFR	Fractional Frequency Reuse
GW	Gateway
HBS	Hub Base Station
HDC	HBS DCO
HSS	Subscriber Station connected to HBS
IF	Intermediate Frequency
IMT	International Mobile Telecommunication
ITU-R	International Telecommunication Union - Radio
LAN	Local Area Network
LE	License Exempt
LE	License Exempt
LOS	Line Of Sight
LTE	Long Term Evolution
LTE-A	LTE - Advanced
MAC	Medium Access Control
MBA-MIMO	Multi-beam assisted MIMO
MCS	Modulation and Coding Scheme
MDP	Markov Decision Process
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MP	Multi Point
MS	Mobile Station
MS/SS	Mobile Station / Subscriber Station
MSE	Mean Square Error
MS-MS	Mobile Station to Mobile Station
MU	Multi-User
NF	Noise Factor
NLOS	Non LOS
NMS	Network Management System
NRM	Network Reference Model
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
OPEX	Operational Expenditure
OR	Opportunistic Radio
OSIC	Ordered Successive Interference Cancellation
PC	Power Control
PER	Packet Error Rate
PHY	Physical Layer
PIC	Parallel Interference Cancelation
PL	Path Loss
P-P, P2P	Point-to-Point
PTX	Transmit Power
QAM	Quadrature Amplitude Modulation
QoS	Quality Of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
RL	Reinforcement Learning
RMS	Root Mean Square
RPE	Radiation Pattern Envelope
RRM	Radio Resource Management
RRM-E	RRM-Entity
RS	Relay Station
RSSI	Received Signal Strength Indicator

Rx	Receive
SDMA	Space Division Multiple Access
SDR	Software Defined Radio
SF	Shadow Fading
SIC	Successive Interference Cancelation
SINR	Signal To Noise And Interference Ratio
SISO	Single Input Single Output
SM	Spatial Multiplexing
SON	Self Organizing Network
STC	Space Time Coding
SU	Single User
TDD	Time Division Duplex
TF	Frame Time
THP	Tomlinson-Harashima Precoding
TTG	Transmit Transition Gap
TTI	Transmission Time Interval
Tx	Transmitter
UE	User Equipment
UL	Uplink
UL/DL	Uplink/Downlink
UMi	Urban Micro Cell
V-BLAST	Vertical-Bell Laboratories Layered Space Time [Code]
VDSL	Very High Bit Rate DSL
VR	Visibility Regions
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
XPIC	Cross Polarization
ZF	Zero Forcing

4 Introduction

The present document presents a new possible wireless BWA network, including heterogeneous elements (a two tier approach), combined use of licensed and license-exempt spectrum, very low delay communications between network elements, enabling the operation of the network MIMO technology.

The description of the networking features is in general done using the WiMAX terminology, however should be no barrier in using the 3GPP network for implementing this network.

5 Architecture for 1 Gbit/s/km^2 network

The architecture presented in the present document represents a number of promising features that contribute to the overall increase in access network capacity and link throughput characteristics. The list includes the following features:

- Multiple access links aggregation;
- Self-Backhauling link aggregation;
- Network MIMO (for Downlink and Uplink);
- Radio Resource Management;
- Direct BS-BS or MS-MS communication.

5.1 Access Stratum Architecture

The present document addresses only the access stratum architecture. The architecture aims to offer a cost efficient capacity density of 1 Gbit/s/km^2. Here, a HBS serves several below-rooftop ABSs, which in turn serve the associated MSs. The HBS possesses several beams which are used to communicate with ABSs in its beam-space. ABSs can communicate with each other via the serving HBS. A topic for further study is the direct ABS-ABS communication while using the air interface.

The Femto-BS and their associated subscribers may also operate in the un-licensed spectrum.

To simplify the presentation, the HBS-ABS links, which are self-backhaul links inside this system, may be named in the present document "backhaul links". This naming should not be understood as HBS backhauling, which is outside of the scope of the present document.

The system presented in the present document has the following basic architecture:

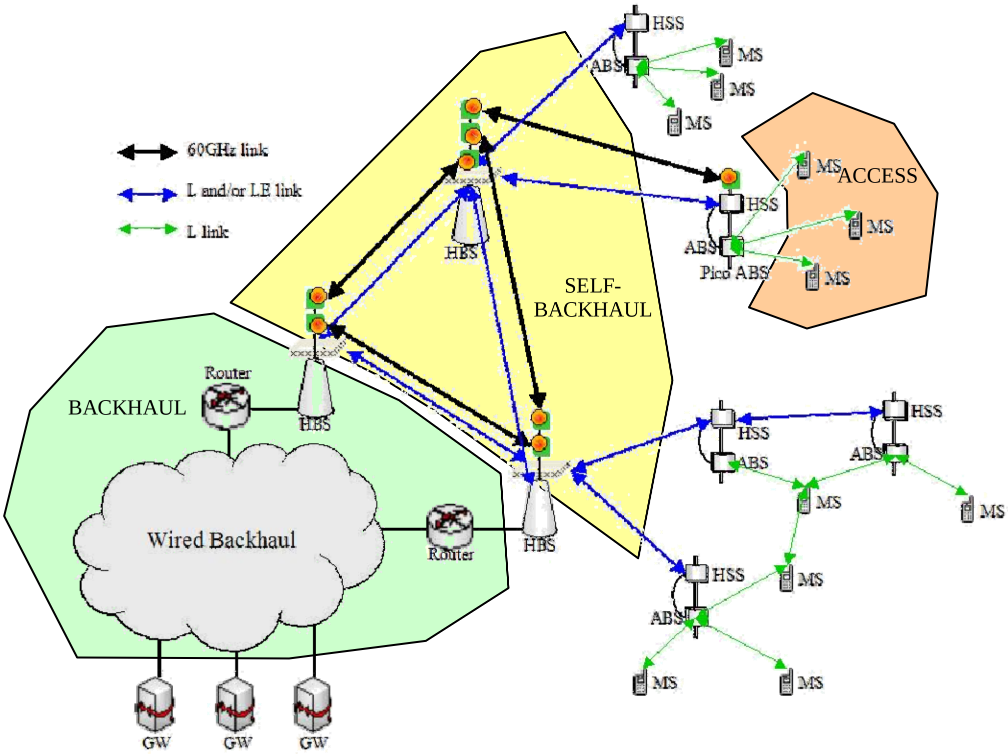


Figure 5.1: Basic architecture

The scheme in figure 5.1 provides an overview of most of the possible wireless links in the present document. At the top level of the architecture, HBSs are directly connected to the wired backhaul. If in some cases a wired link could not be done, this link should be replaced by LE high data rate connectivity.

An in-band backhaul link and a LE link between HBSs may not be systematically done but could offer additional networking capacities and an alternative, in case of a router failure for example.

At the ABS location there are two elements, which are the HSS and the ABS. The HSS component is associated to an HBS or to another HSS (for direct communication and collaborative MIMO). ABS provides connectivity for the BWA users.

To increase the coverage or to provide a larger throughput in a given area exists the possibility to deploy additional stations called pico-ABS. Those stations are basically similar to ABSs as they are providing connectivity to BWA users.

The lower level of the architecture shows mobile station connectivity possibilities. MS connects itself to ABS as in the standard P-MP architecture, but can also directly connect one to each other, and associate with two ABSs for MIMO support.

5.2 Simplified Network Architecture

The simplified network architecture of a BWA system is summarized in figure 5.2.

The following notations are used for the reference points:

A1 - GW to GW reference point.

B2 - GW to HBS reference point.

C3 - HBS to ABS reference point.

D4 - ABS to ABS reference point.

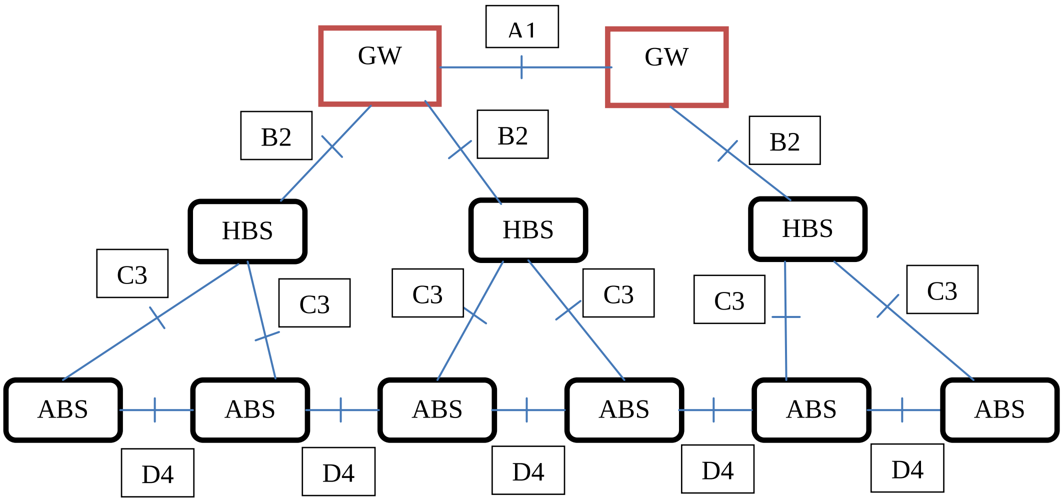


Figure 5.2: Network Architecture

The system-specific of interfaces in figure 5.2 are:

A1: Reference Point A1 consists of the set of Control and Bearer Plane protocols originating/terminating in GWs that coordinate MS mobility between GWs.

B2: Reference Point B2 consists of the set of Control Plane message flows and Bearer Plane data flows between the base stations and the GW.

C3, D4: Reference Points C3, D4 consists of the set of Control Plane message flows and optionally Bearer Plane data flows between the base stations to ensure fast and seamless handover. The Bearer Plane consists of protocols that allow the data transfer between Base Stations involved in handover of a certain MS. In addition, C3 can carry RRM control messages for the joint usage of the spectrum by HBS and ABS.

For the purpose of this discussion, it is important to note that according to the network architecture each BS may be engaged in signalling transactions and traffic exchange with multiple GWs and vice versa.

6 Access Stratum Functionality

Those basic elements of the access operation which are characteristic for the studied system are presented in continuation.

6.1 Topology

The system deployment will use the ABSs located below roof-tops and HBSs located either below or above rooftops.

The ABS deployment can have two flavours:

- ABSs located on streets;
- ABSs located in those areas with insufficient radio coverage.

Two deployment variants, named "cross" and "square", are proposed for deployment.

6.2 Physical Deployment

6.2.1 Basic Cross and Square Deployments for Access

The basic cross and square deployments, using four frequency channels of 10 MHz each for TDD or 2 × 5 MHz for FDD, are illustrated in figures 6.1 and 6.2. These deployments assume a Manhattan-like grid, having a block raster of 90 m. The figures illustrate a frequency planning strategy, having as scope to minimize the inter-ABS interference between adjacent HBS cells.

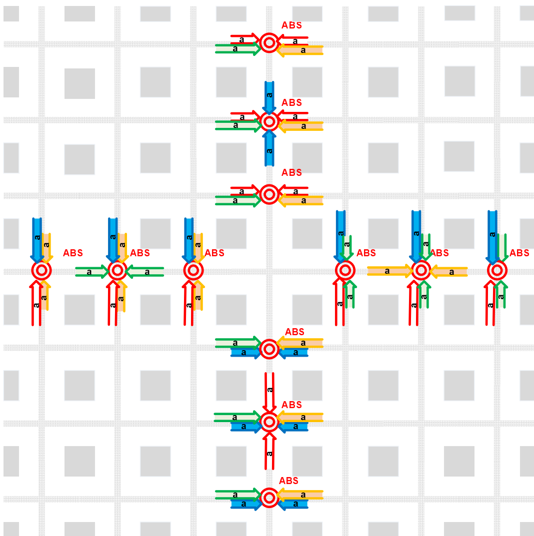


Figure 6.1: Cross deployment

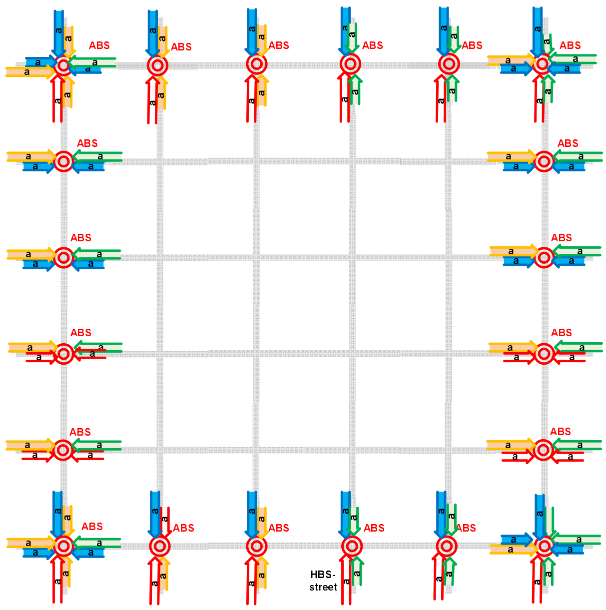


Figure 6.2: Square deployment

6.2.2 Combined Access and Backhauling

The following figures show the combined access and backhauling. In figure 6.3 the HBS is located below roof-top while in figure 6.4 the HBS is located above roof-top. In figure 6.3 there are still coverage holes which are covered by an above-rooftop HBS operating in 5 GHz.

In the figures below, "a" means access, while "b" means backhaul. One color is used for each of the four available frequency channels.

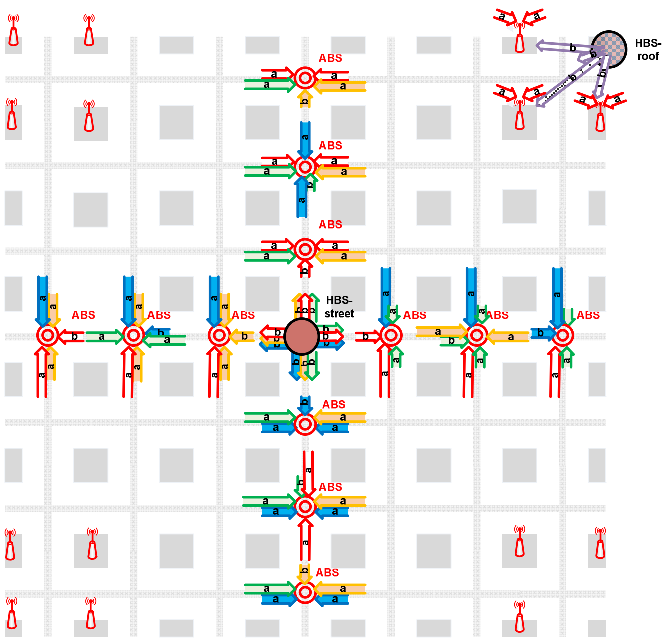


Figure 6.3: HBS under roof-top for cross topology

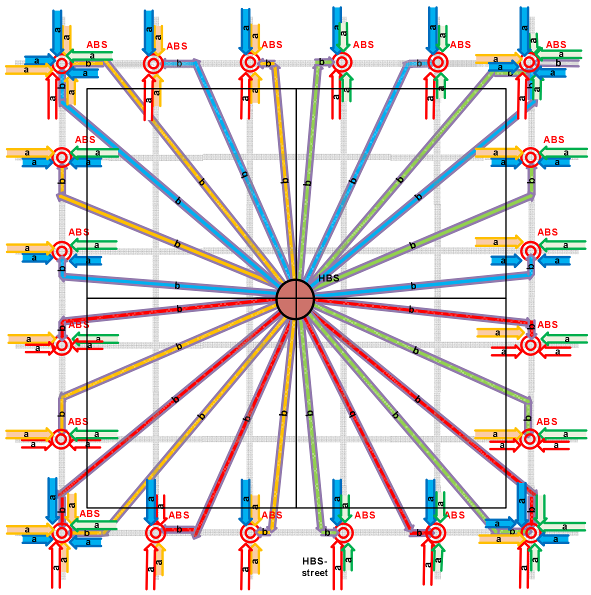


Figure 6.4: HBS above roof-top for square topology

Figure 6.5 indicates a combined deployment of a self-backhauling cell at 2,6 GHz/3,5 GHz, with HBS above roof-top and a 60 GHz self-backhaul, deployed in LOS at street level.

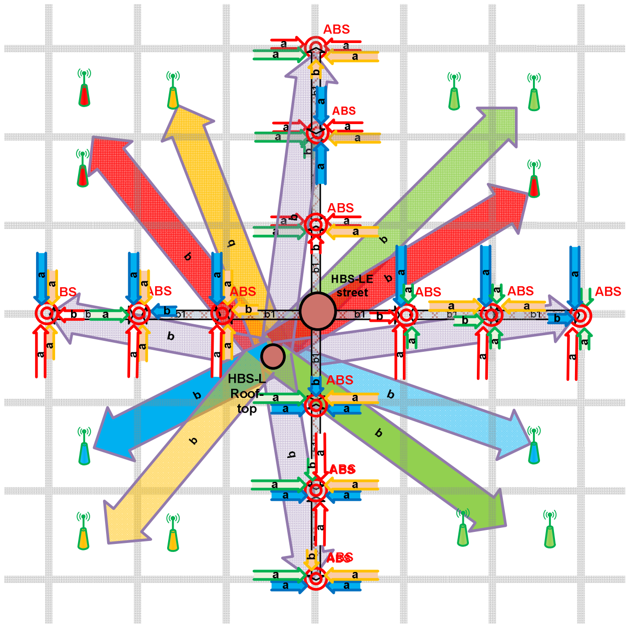


Figure 6.5: Combined in-band and 60GHz backhaul

NOTE: In all the above figures, the sophisticated frequency planning for allowing a high reuse of the four available frequencies in the licensed spectrum.

In figure 6.6 is shown an example of the multi-cell deployment when the HBS is placed over the roof. Note the de-lineated placement of HBS, to create a more pronounced special isolation between antenna beams. Un-regular beam-widths may be needed, due to the ABS placement on the main cross directions; in other directions the capacity requirement is lower such that larger antenna beam widths can be used.

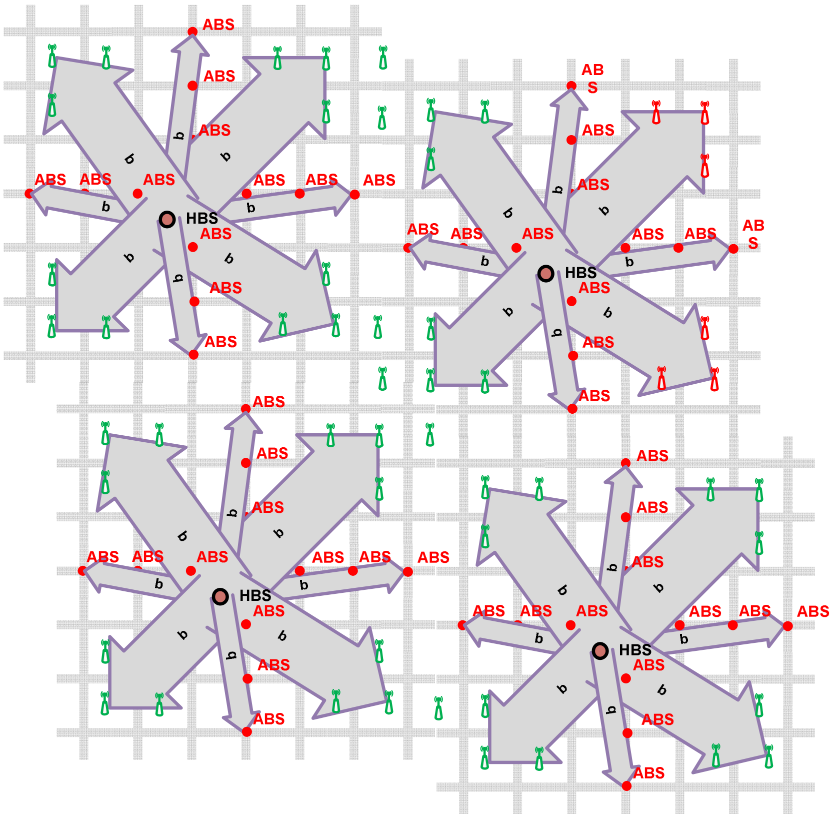


Figure 6.6: Star topology, HBS above roof-top

6.2.2.1 Square Topology, HBS above Roof-Top

In figure 6.7 is shown the multi-cell deployment in the case of the square topology. This deployment has some properties of reducing the interference between beams arriving from adjacent HBS cells, if spatial separation is used.

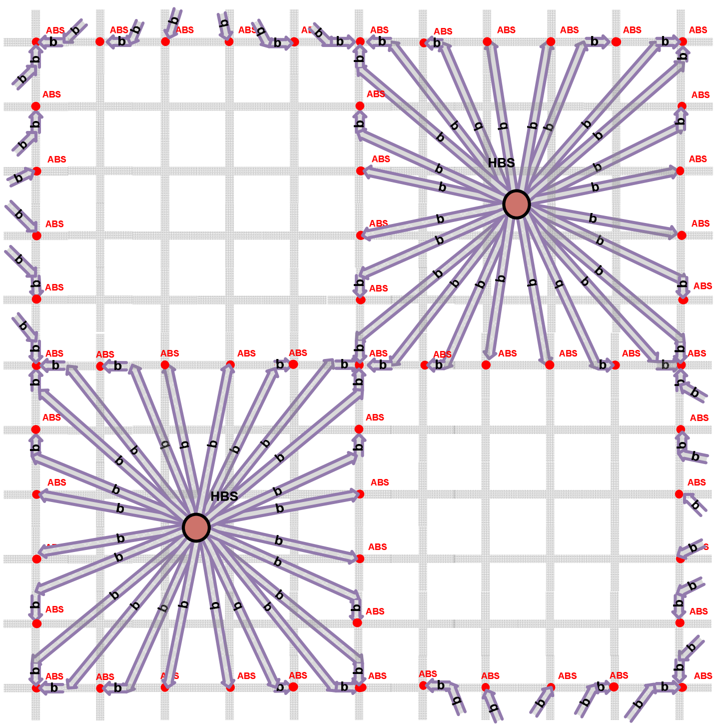


Figure 6.7: Square topology, HBS above roof-top

6.3 Antennas

The spatial multiplexing is an important technology for achieving very high data rates in the wireless networks. While in other access network the antennas illuminate the full sector, in this system the HBS antenna is composed from multiple cross-polarized adjacent narrow beams.

The provision of high capacity densities in the system self-backhaul can be achieved if the HBS is able to generate a large number of fixed narrow beams. In the described system this technique is used to provide wireless backhaul to a large number of ABSs, which then serve user terminals. The HBS can create multiple fixed narrow beams with the use of an antenna array fed by a Butler matrix (BM). A BM is a passive external circuit operating at microwave frequencies having N ports feeding/receiving signals to/from the antennas and n ports feeding/receiving signals to/from the RF chains [i.2]. A BM consisting of phase shifters, quadrature hybrids and couplers, essentially implements a fixed RF beamformer creating n narrow beams, where $n \leq N$. This fixed beamformer allows the application of MIMO techniques in the beam domain as opposed to the conventional antenna domain; in order to minimize inter-beam interference the received signals at the n ports of the BM are jointly processed in the baseband and this concept is defined as *multi-beam assisted MIMO* (MBA-MIMO) [i.2].

Such an antenna may use six dual-polarized beams in a 90 degrees sector. An example of the antenna characteristics taken from is presented in figure5.3.

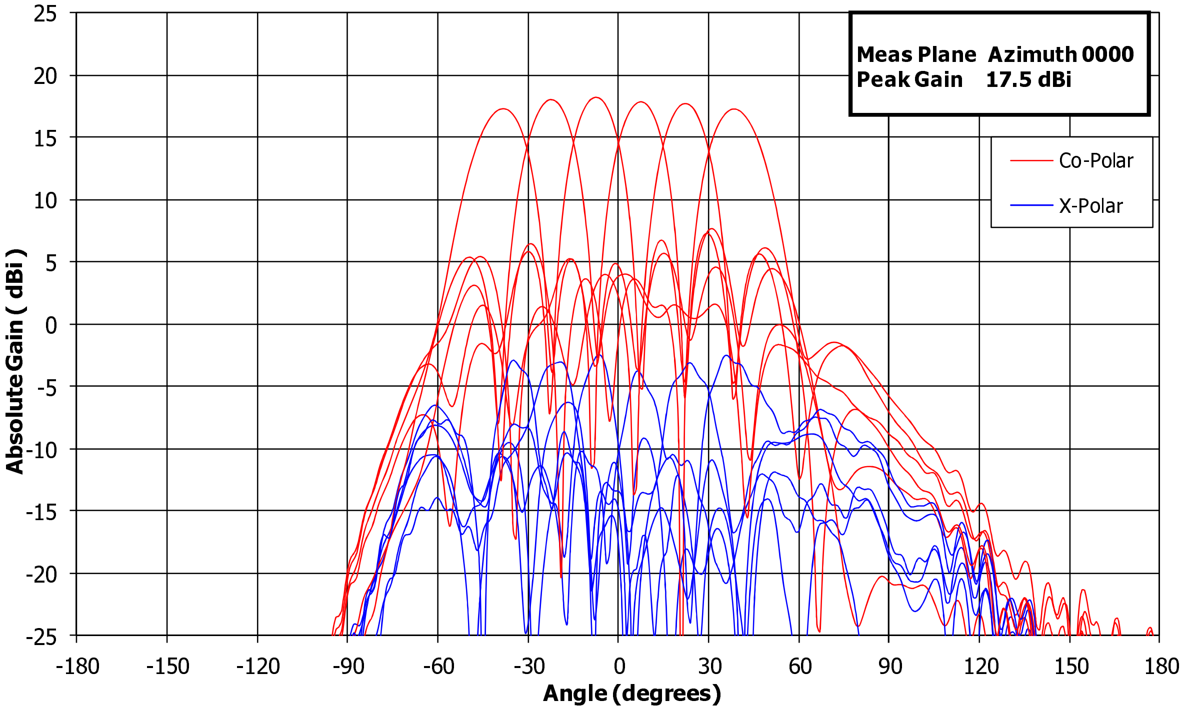


Figure 6.8: Azimuth characteristics of a multi-beam antenna

It should be noted that the maximum system performance is obtained when the MIMO technology is used in conjunction with such multi-beam antenna.

6.4 Multi-beam Assisted MIMO

6.4.1 Overview

Multi-beam assisted MIMO (MBA-MIMO) is employed on the HBS - ABS links in conjunction with the multi-beam antenna. Hence it applies at frequencies relevant to the multi-beam antenna, i.e. in the licensed bands and at the license-exempt bands below 6 GHz. It does not apply to 60 GHz backhauling.

The principle is to apply multi-user MIMO techniques in the beam-space of the multi-beam antenna rather than on a per-element basis. This requires signal processing modules to be implemented in the HBS which we refer to as joint beam processing, and which is analogous to the signal processing techniques employed at the base-station end of a multi-user MIMO cellular system. The ABS will also be equipped with multiple antennas, and MIMO processing techniques will also be applied there, in particular for interference avoidance from other HBSs, but also to exploit polarization multiplexing, given that the HBS antenna also allows dual polarized operation.

The advantage of the multi-beam antenna as compared with an array antenna at the HBS of equivalent size as applied to the multi-user system formed by the ABSs served by the HBS is that it makes the multi-user channel much more sparse, in the sense that signals related to one user impinge on only a small number of HBS beams. In contrast in a multi-user MIMO system employing a conventional array signals from all users in a given quadrant impinge on all antenna elements in the array. This reduces the complexity of the signal processing required and improves the numerical stability of the algorithms. It also simplifies and improves the performance of channel estimation.

In the following two clauses we review the functions required at HBS and ABS ends of the link for operation in the licensed band for uplink and for downlink operation. We then consider additional requirements for use in unlicensed bands for mitigation where possible of other-user interference.

Note that at the ABS location will be three antenna types:

- oriented towards HBS, actually an HSS antenna, used for the backhauling network in lower frequencies;
- oriented towards MSs, serving the access network in the lower frequencies;
- For the P-P link at 60 GHz.

6.4.2 Uplink Operation in Licensed Bands

The ABS functions are listed below:

- *Polarisation multiplexing*: if the ABS is equipped with dual polarized antenna elements (±45° to match those at the HBS antenna), the data to be transmitted on the uplink may be multiplexed between the two polarizations, thereby doubling the available capacity.
- *Precoding*: if the ABS is equipped with multiple (possibly dual polarized) antenna elements to serve the link to the HBS additionally precoding may be applied across these antennas. Since most ABSs are likely to be served primarily by one HBS beam, it is likely that only one data stream ("layer" in 3GPP-LTE terminology) will be available, so the precoding will consist in selection of an optimum beam-former. However the architecture presented in the present document allows joint beam processing to be applied at the HBS for reception on the uplink, and in some cases it may be possible and advantageous to allow transmission on multiple layers. Note that this will require channel state information (CSI) which may be obtained from a downlink pilot transmission or by means of feedback from the HBS via a control channel on the downlink. Note that in the present document CSI is not used in a mode similar to existing 3GPP standards.
- *Interference mitigation*: if the ABS transmission may be liable to cause interference to HBSs serving neighbouring cells, the precoder selection may take account of the interfering signals received from these HBSs on the downlink, so as to minimise interference caused to them. This may require the ABS to be able to decode pilot signals from such HBSs. It also assumes reciprocity of these links, which is likely to hold if uplink to desired HBS and downlink from interfering HBS is at the same frequency. Even in the absence of reciprocity, sufficient information may be available to allow interference mitigation.
- *Modulation and coding*: the ABS will provide appropriate modulation and coding according to CSI feedback from the HBS.
- *Channel estimation support*: the ABS will need to transmit pilot signals to the HBS to allow estimation of the ABS - HBS channel response. Note that it is likely that the backhaul links will be relatively slowly time-varying, so the pilot overhead required for this purpose is likely to be small.

The HBS functions are listed below:

- *Joint beam processing*: signal processing for multi-user detection, to separate the signals originating from different ABSs and received on multiple beams of the HBS. These may be linear - zero forcing (ZF) or minimum mean square error (MMSE) or non-linear - successive interference cancellation (SIC), ordered successive interference cancellation (OSIC) or parallel interference cancellation (PIC) - and may also involve iterative processing with the FEC decoder. This may also involve separation of multiple data streams from one ABS, if these are provided.

- *Polarisation demultiplexing*: it will also incorporate demultiplexing of the dual polarised signals, using the dual polar beams of the HBS antenna.

- *Demodulation and decoding*: demodulation and FEC decoding will be performed: if iterative techniques are to be applied, soft input, soft output (SISO) decoding will be required.

- *Channel estimation*: the HBS will estimate the channel response from all antennas of all ABSs to the beams of the HBS which receive significant power, on both polarisations. The resulting CSI will be signalled back to the ABS via a control channel on the downlink.

6.4.3 Downlink Operation in Licensed Bands

The HBS functions are listed below:

- *Multi-user precoding*: this is the dual of the joint beam processing for multi-user detection performed on the uplink; data for the ABSs is precoded, exploiting CSI for all HBS - ABS links. Precoding may be linear or non-linear, using Tomlinson-Harashima precoding (THP).

- *Polarisation multiplexing*: again, if the ABS is equipped with dual polarised antennas, data on the downlink also may be multiplexed across the polarisations at the HBS.

- *Interference mitigation*: if the HBS may be liable to cause interference to ABSs served by neighbouring HBSs, precoder selection may take account of interference received at the HBS from such ABSs, so as to minimise interference caused to them. The same issues of reciprocity apply here as in bullet above.

- *Modulation and coding*: the HBS will provide appropriate modulation and coding according to CSI feedback from the ABS.

- *Channel estimation support*: the HBS will need to transmit pilot signals to the ABS to allow estimation of the HBS - ABS channel response.

The ABS functions are listed below:

- *Maximum ratio combining*: of signals on the multiple ABS antennas. Nonlinear processing will also be required if non-linear precoding is employed at the HBS.

- *Interference mitigation*: this should also take account of interference from neighbouring HBSs: the combining criterion should be max-SINR beamforming, again with nonlinear processing if appropriate.

- *Polarisation demultiplexing*: if the ABS is equipped with dual polar antennas, the two data streams should be demultiplexed.

- *Demodulation and decoding*: demodulation and FEC decoding will be performed: for iterative decoding/detection, soft input, soft output (SISO) decoding will be required.

- *Channel estimation*: the ABS will estimate the channel response to all antennas of the ABSs from the beams of the HBS from which significant power is received, on both polarisations. The resulting CSI will be signalled back to the HBS via a control channel on the uplink.

6.4.4 Interference Mitigation in Lower LE Bands (< 6 GHz)

Backhaul operation in the lower LE bands will require the same functions as for the licensed bands, as described in the previous two clauses. However it may additionally require, or benefit from, interference mitigation for signals from other unlicensed users sharing the same band. This will additionally require the following functions, on both up- and downlink:

- *Interference estimation*: estimation at the receiver of the correlation matrix of the interference, to enable minimisation of its effect. This will form part of the CSI to be fed back to the transmitter on the control channel. Note that interference may vary relatively rapidly, and is not synchronised to the wanted signals, so means should be provided for the receiver to estimate this interference at regular intervals.

- *Optimum signal combining*: taking account of this interference to maximise the SINR of the received signal at the receiver. Note that since the format of the interfering signal is unknown, non-linear interference cancellation techniques are probably not feasible.

- *Optimum precoding*: the precoder selection at the transmitter should take account of the CSI regarding this interference fed back from the receiver.

6.5 Collaborative MIMO, Network MIMO Support

6.5.1 Introduction

In this clause, the functional blocks for each cooperation configuration to be exploited in this system are listed and briefly described. This is particularized for the three basic configurations considered in the present document, namely collaborative MIMO (cooperation between MSs), network MIMO (cooperation between ABSs), and a hybrid scheme (cooperation between both MSs and ABSs). The general system architecture considered in this clause is depicted in figure 6.9.

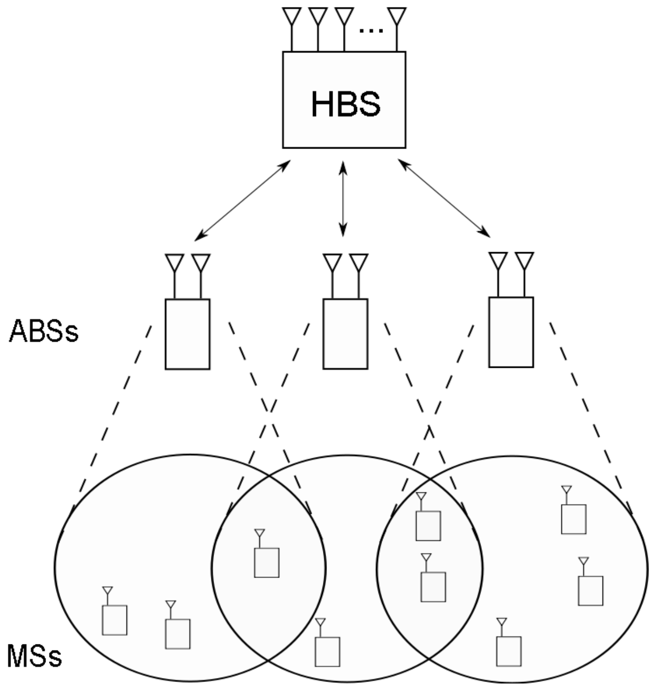


Figure 6.9: General system architecture for DL collaborative MIMO

6.5.2 Collaborative MIMO

In collaborative MIMO several MSs are allowed to cooperate among them to enhance the quality of the transmission towards or from the corresponding ABS, i.e. the access links.

Uplink transmission from ABS to HBS

In uplink collaborative MIMO transmission, several MSs belonging to the same coverage area of a single ABS are grouped together to cooperate and enhance the transmission towards such ABS, i.e. the quality of the access links (see figure 6.10). This cooperative transmission is carried out according to the following functional blocks:

- *MSs-ABS channel estimation*: the ABS estimates the MIMO channel response corresponding to the uplink transmission from each MS in its coverage area to such ABS. Based on this, the ABS can build the MIMO channel matrix for the uplink from each MS.
- *MS-MS channel estimation*: in a second phase, each MS in the coverage area transmits a training sequence, whereas all the other MSs estimate the MIMO channels from such transmitting MS, as far as the link between the transmitting MS and the MS estimating the channel is not blocked by any object. Based on this, each MS can construct the MIMO channel matrices corresponding to the transmission from all the other MSs in the coverage area.
- *CSI transmission towards the ABS*: all the MSs transmit to the ABS the channels estimated from all the other MSs in the same coverage area.
- *Grouping of cooperating MSs*: based on all the information concerning the channel responses, the ABS decides how to group the MSs, so that the MSs in the same group will cooperate to enhance the transmission in the uplink. Additionally, the ABS will allocate the radio-resources to the different groups.
- *Broadcast of the grouping strategy and scheduling parameters*: the ABS broadcasts the information concerning the grouping of the MSs and the scheduling to be used to all the MSs in the corresponding coverage area.
- *Information sharing between MSs*: the MSs in a single group share among them the information symbols to be transmitted and adjust the corresponding synchronism parameters, if needed.
- *Uplink MS transmission*: finally, all the MSs in a single group transmit their information symbols according to some cooperative MIMO strategy, such as distributed space-time coding, distributed beamforming, etc. and following the indications provided by the ABS concerning the allocation of radio resources.

The control information to be used in this scheme is related with the group configurations, the MIMO technique to be applied, the management and allocation of radio resources, and synchronization aspects.

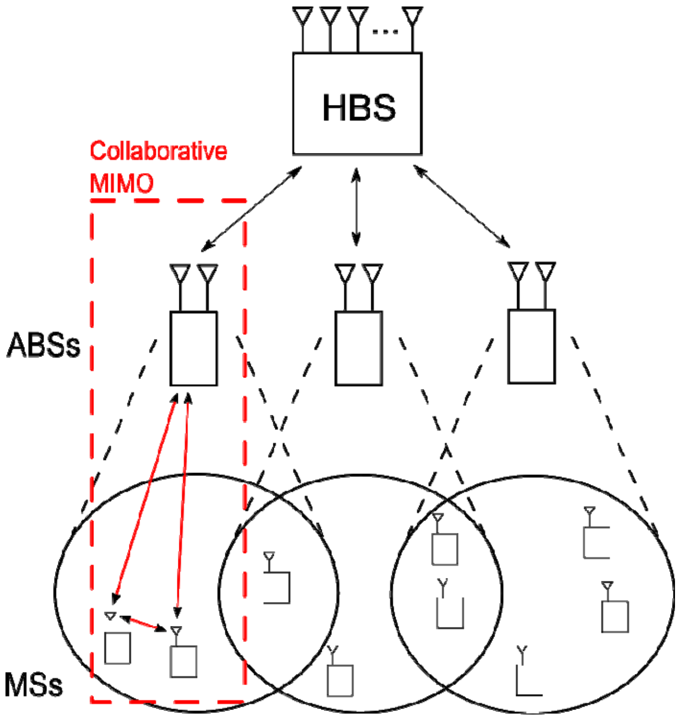


Figure 6.10: Collaborative MIMO in the Access Uplink/Downlink

Downlink transmission:

In downlink collaborative MIMO transmission, several MSs belonging to the same coverage area of a single ABS are grouped together to cooperate and enhance the reception from such ABS, i.e. the quality of the access links (see figure 6.10). This cooperative reception is carried out according to the following functional blocks:

- *ABS-MSs channel estimation*: each MS estimates the MIMO channel response corresponding to the downlink transmission from the ABS. Based on this, each MS can build its MIMO channel matrix for such link.
- *MS-MS channel estimation*: in a second phase each MS in the coverage areas transmits a training sequence, whereas all the other MSs estimate the MIMO channels from such transmitting MS, as far as the link between the transmitting MS and the MS estimating the channel is not blocked by any object. Based on this, each MS can construct the MIMO channel matrices corresponding to the transmission from all the other MSs in the coverage area.
- *CSI transmission towards the ABS*: all the MSs transmit to the ABS the channels estimated from all the other MSs in the same coverage area.
- *Grouping of cooperating MSs*: based on all the information concerning the channel responses, the ABS decides how to group the MSs, so that the MSs in the same group will cooperate to enhance the reception in the downlink. Finally, the ABS will allocate the radio-resources.
- *Broadcast of the grouping strategy and scheduling parameters*: the ABS broadcasts the information concerning the grouping of the MSs and the scheduling to be used to all the MSs in the corresponding coverage area.
- *Transmission from HBS to ABS*: the HBS transmits to the ABS through the self-backhauling link the information that has to be sent to the MSs of such ABS. The ABS chooses which MIMO technique should be used for the downlink transmission from the ABS to the MSs.
- *Downlink transmission*: the ABS transmits the information intended for the MSs using the previously decided MIMO technique.
- *Signal detection*: finally, the MSs carry out the detection of the signal transmitted by the ABS. Depending on the applied MIMO technique, it would be possible that the MSs exchange some kind of information (e.g. detected symbols or received signals) to perform cooperative detection.

6.5.3 Network MIMO

In network MIMO several ABSs are allowed to cooperate among them to enhance the transmission towards or from the MSs, i.e. the quality of the access links (see figure 6.11).

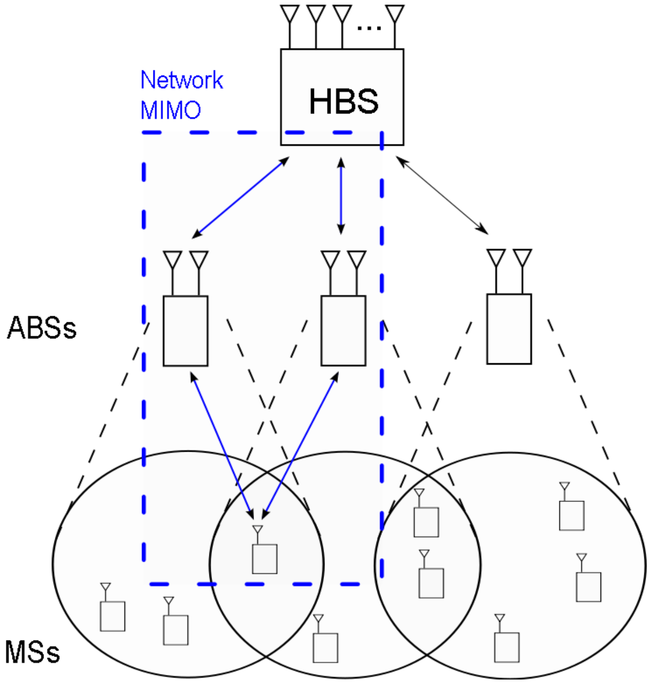


Figure 6.11: Network MIMO in both the Access Uplink and Downlink

Uplink transmission:

In uplink network MIMO transmission several ABSs cooperate to enhance the reception of the signal transmitted by a single MS through the access link. Obviously, such MS should be within the coverage areas of all the ABSs that are cooperating as it can be seen in, e.g. figure 6.11. This cooperative transmission is carried out according to the following functional blocks:

- *MS-ABSs channel estimation*: the ABSs estimate the MIMO channel responses corresponding to the uplink transmission from the MS whose signal has to be detected. Based on this, each ABS can build the MIMO channel matrix for the uplink from the MS.
- *Uplink MS transmission*: the MS transmits the information signal, which is received by all the ABSs that are intended to cooperate and using the previously decided MIMO technique.
- *Transmission from ABSs to HBS*: the ABS relays the received signals to the HBS through the self-backhauling links. Observe that, to reduce the backhaul overhead, distributed compression of the MS signals at the ABSs might be eventually performed. The ABSs also transmit the MIMO channel responses corresponding to the access links from the MS to such ABSs.
- *Signal detection*: finally, the HBS carries out the detection of the signal transmitted by the MS by jointly using all the received signals at the cooperating ABSs and exploiting the knowledge of the MIMO channel responses corresponding to the access links from the MS to the ABSs.

The control information to be used in this scheme is related with the MIMO technique to be applied, the management and allocation of radio resources, and synchronization aspects.

Downlink Transmission:

In downlink network MIMO transmission several ABSs cooperate to enhance the transmission towards a MS. Obviously such MS should be within the coverage areas of all the ABSs that are cooperating. This cooperative transmission is carried out according to the following functional blocks:

- *ABSs-MS channel estimation*: the MS estimates the MIMO channel responses corresponding to the downlink transmission from the ABSs that are cooperating. Based on this, the MS can build the MIMO channel matrices for such links.

- *Transmission from HBS to ABSs*: the HBS transmits to the ABSs through the self-backhauling links the information that has to be sent to the MS for which the ABSs are cooperating. The HBS also indicates which MIMO technique should be used for the downlink cooperative transmission from the ABSs to the MS.
- *Downlink transmission*: the cooperating ABSs transmit the information intended for the MS using the previously decided MIMO cooperative technique.
- *Signal detection*: finally, the MS carries out the detection of the signal transmitted by the cooperating ABSs. This is done by using the received signal at the MS and exploiting the knowledge of the MIMO channel responses corresponding to the access links from the ABSs to the MS.

The control information to be used in this scheme is related with the MIMO technique to be applied, the management and allocation of radio resources, and synchronization aspects.

6.6 Hybrid MIMO Schemes

In a hybrid scheme we consider the situation where several MSs (more than one) are in the coverage area of more than one ABS at the same time. In this situation both the MSs and the ABSs could cooperate among them to enhance the quality of the transmission through the access links (see figure 6.12).

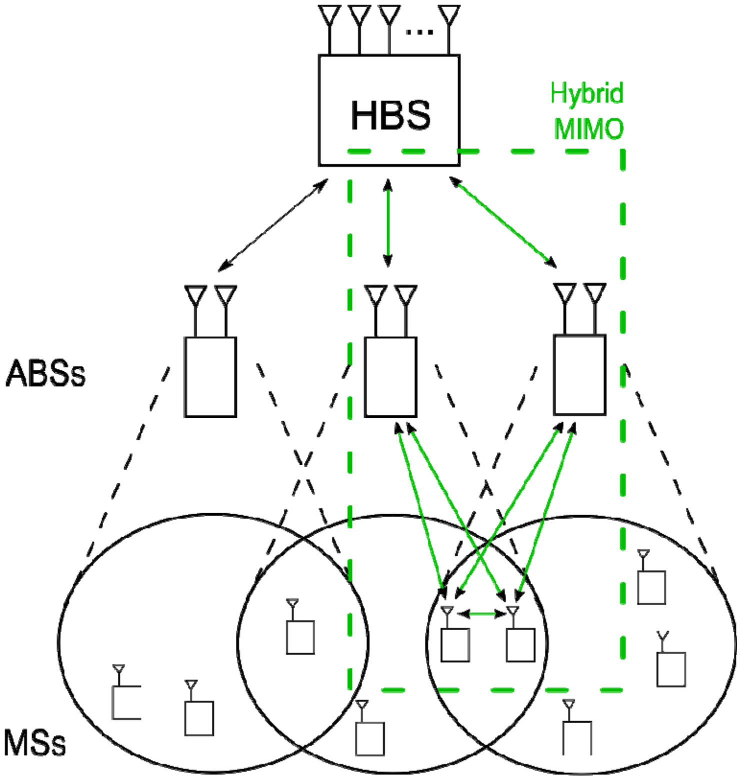


Figure 6.12: Hybrid scheme in the Access Uplink/Downlink

Uplink Transmission:

In the hybrid uplink transmission several MSs are grouped together in order to cooperate in the transmission towards the corresponding cooperating ABSs and enhance the quality of the access links. Then, the received signals at the cooperating ABSs are sent to the HBS so that such HBS can carry out the final signal detection. This cooperative transmission is carried out according to the following functional blocks:

- *MSs-ABSs channel estimation and forwarding of the CSI to the HBS*: the ABSs estimate the MIMO channel responses corresponding to the uplink transmission from each MS in their coverage areas to such ABSs. Based on this, the ABSs can build the MIMO channel matrices for the uplink from each MS. The ABSs then forward such channel matrices to the HBS.

- *MS-MS channel estimation*: in a second phase each MS in the coverage areas transmits a training sequence, whereas all the other MSs estimate the MIMO channels from such transmitting MS, as far as the link between the transmitting MS and the MS estimating the channel is not blocked by any object. Based on this, each MS can construct the MIMO channel matrices corresponding to the transmission from all the other MSs in the coverage area.

- *CSI transmission towards the ABSs and forwarding to the HBS*: all the MSs transmit to the ABSs the channels estimated from all the other MSs in the same coverage area. Then, the ABSs forward such channel estimates to the HBS.

- *Grouping of cooperating MSs and ABSs*: based on all the information concerning the channel responses, the HBS decides how to group the MSs, so that the MSs in the same group will cooperate to enhance the transmission in the uplink. The HBS also decides which ABSs will cooperate together. Finally, the HBS will allocate the radio-resources. All this information is sent from the HBS to the ABSs.

- *Broadcast of the grouping strategy and scheduling parameters*: the ABSs broadcast the information concerning the grouping of the MSs and the scheduling to be used to all the MSs in the corresponding coverage area.

- *Information sharing between MSs*: the MSs in a single group share among them the information symbols to be transmitted and adjust the corresponding synchronism parameters, if needed.

- *Uplink MSs' transmission*: all the MSs in a single group transmit their information symbols according to some cooperative MIMO strategy, such as distributed space-time coding, distributed beamforming, etc. and following the indications provided by the ABSs concerning the allocation of radio resources.

- *Transmission from ABSs to HBS*: the ABSs relays the received signals to the HBS through the self-backhauling links.

- *Signal detection*: finally, the HBS carries out the detection of the signal transmitted by the cooperating MSs by jointly using all the received signals at the cooperating ABSs and exploiting the knowledge of the MIMO channel responses corresponding to the access links from the MS to the ABSs.

The control information to be used in this scheme is related with the group configurations, the MIMO technique to be applied, the management and allocation of radio resources, and synchronization aspects.

Downlink Transmission:

In the hybrid downlink transmission several MSs are grouped together in order to cooperate in the reception from the corresponding cooperating ABSs and enhance the quality of the access links. This cooperative transmission is carried out according to the following functional blocks:

- *ABSs-MSs channel estimation*: the MSs estimate the MIMO channel responses corresponding to the downlink transmission from the ABSs that are cooperating. Based on this, the MSs can build the MIMO channel matrices for such links.

- *MS-MS channel estimation*: in a second phase each MS in the coverage areas transmits a training sequence, whereas all the other MSs estimate the MIMO channels from such transmitting MS, as far as the link between the transmitting MS and the MS estimating the channel is not blocked by any object. Based on this, each MS can construct the MIMO channel matrices corresponding to the transmission from all the other MSs in the coverage area.

- *CSI transmission towards the ABSs and forwarding to the HBS*: all the MSs transmit to the ABSs the channels estimated from all the other MSs in the same coverage area. Then, the ABSs forward such channel estimates to the HBS.

- *Grouping of cooperating MSs*: based on all the information concerning the channel responses, the HBS decides how to group the MSs, so that the MSs in the same group will cooperate to enhance the reception in the downlink. Finally, the HBS will allocate the radio-resources. All this information is sent from the HBS to the ABS.

- *Broadcast of the grouping strategy and scheduling parameters*: the ABS broadcasts the information concerning the grouping of the MSs and the scheduling to be used to all the MSs in the corresponding coverage area.

- *Transmission from HBS to ABSs*: the HBS transmits to the ABSs through the self-backhauling links the information that has to be sent to the MSs for which the ABSs are cooperating. The HBS also indicates which MIMO technique should be used for the downlink cooperative transmission from the ABSs to the MSs.
- *Downlink transmission*: the cooperating ABSs transmit the information intended for the MSs using the previously decided MIMO cooperative technique.
- *Signal detection*: finally, the MSs carry out the detection of the signals transmitted by the cooperating ABSs. This is done by using the received signals at the MSs and exploiting the knowledge of the MIMO channel responses corresponding to the access links from the ABSs to the MSs. Depending on the applied MIMO technique, it would be possible that the MSs exchange some kind of information (e.g. detected symbols or received signals) to perform cooperative detection.

6.7 Radio Resource Management

The radio resource if a multi-dimentional element, including:

- Licensed spectrum resource, with the resolution of operating frequency channels, used in the access operation and self-backhauling operation.
- License-exempt frequency bands, typically 5 GHz and 60 GHz, used in the self-backhauling operation.
- Time resource, with the allocation resolution of a subframe within a wireless frame; the time resource can be distributed between different ABSs, HSSs and HBSs for collaborative interference cancellation.
- Spatial resource, used in MIMO systems.

RRM procedures specific for our system will be presented in continuation.

6.7.1 Dynamic Frequency Band Allocation

The performance of the system can be improved if the static or quasi-static assignment is made dynamic and adaptable. Furthermore, a centralized approach can be replaced by a distributed approach which lowers control traffic further and aids system scalability. Said approaches are dealt with in this clause.

6.7.1.1 Selection Principle

Once a set of frequencies is defined, a decision can be done continuously either in a distributed way or using a centralized RRM-Entity (RRM-E). Distributed strategy means to directly choose the frequency channel using local information only, whereas the centralized solution takes into account information collected in some group of RAN entities allowing to minimize interference. As per figure 6.13, the objective is to consider two kinds of HSS deployments, each one associated with two ABSs radiating horizontal or vertical beams. This ensures separation of the access frequency pool for those two orientations, and for each direction avoids reuse of the same frequency for two parallel and adjacent beams. This solution offers an improvement for interference not visible at ABS positions but visible at specific possible MS locations as exemplified in figure 6.13.

In figure 6.13, the co-located ABS and HSS can receive in the same time from HBS, respectively MS. If the street reflections are such that the directional antennas cannot isolate the interference, the reception of the MS or HBS transmissions can be interfered respectively by HBS or MS transmissions.

The RRM-E should be responsible of allocating frequency channels such to enable the reuse of the frequency only when possible.

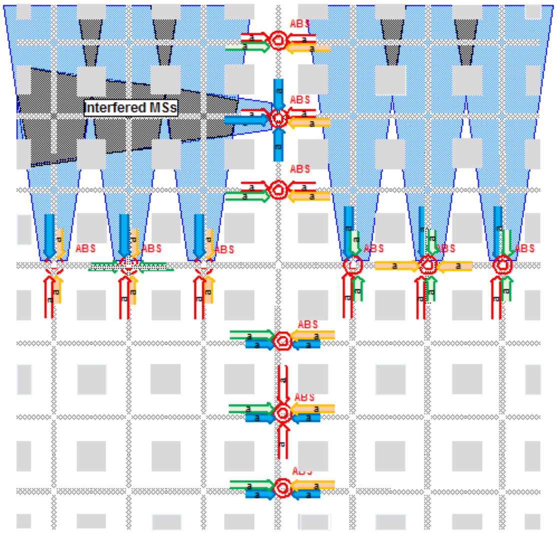


Figure 6.13: Interferences at mobile nodes level

The centralized RRM-Entity can be co-located with the HBS and is responsible for its own square grid management. The centralized RRM-Entity can also be responsible for updating channel state information (typically obtained from sounding, scanning or sniffing functionalities, and potentially including RSSI level, CINR, BER and PER), local adjustments if required, and coordination with other nearby RRM-Entities. The RRM-Entity is supposed to have knowledge of nodes' locations, to have some computation capacities and to be able to exchange messages with nodes it allocates resources for, as well as peer RRM-Entities.

To use the frequency selection plan, the centralized RRM-Entity firstly needs to be aware of the possible frequency channels available at all instances. For this, the ABSs locally analyse their surrounding channel status; results above a certain margin are incorporated into a frequency pool specific to the given ABS. The RRM-Entity collects all of these and, giving priority to the ABS with smallest frequency pools, allocates one frequency channel to each of it.

Based on the same principles, the RRM-Entity also decides on the frequency channel assignment for each antenna beam at the HBS. The communication links between the HBS and the HSS, based on the system architecture, are crucial and should be prioritized at any cost. If possible, back-up links at 60 GHz should be installed to minimize risks on the links using the access spectrum, which can then be considered as a backup solution with lower power, and lower quality link budget.

In a possible RRM implementation, in a first phase, the channel information is reported from ABS, HSS and HBS to the RRM-E. As indicated above, this information can include different parameters enabling evaluation of the channel state. The RRM-E proceeds with a first frequency channel allocation and then should check after every frequency allocation procedure cycle if each link received a specific channel allocation. Three possible cases then occur:

1) More channels available than necessary; the RRM-E continues to allocate the remaining channels as secondary choices for most critical links.

2) No more channel allocation to perform; the RRM-E transmits the allocated bands to each node in the network.

3) Not enough channels available to allocate one to each link, some of it should be freed or reused to finish frequency planning. Possibilities are to:

   - remove channel allocation from dual link (60 GHz + WiMAX);
   - use a more aggressive spatial reuse strategy (lower margins);
   - reduce bandwidth from specific low priority links.

The RRM-E will finally send the channel configuration once each channel is allocated to a given link.

As an extension of the RRM-E, it can also be considered that the 60 GHz links channel selection can be done on the same basis. In this case, the available frequency pools should be considered as an extension of the station where this 60 GHz link is plugged, and additional deployment information should be considered.

6.7.2 Self-Organizing Frequency Allocation

In order to automatically proceed with the frequency selection, a minimum connectivity should be available.

At the network initialization phase, the HBS makes a scan (basically realizing signal level measurement and estimating error rates for a given link) to identify the best frequency channel it can use. The HSS can then connect even if frequency channels are not optimized: the objective being only to create a first connection.

After this initial step and the use of a fine frequency allocation, the whole system should also be able to adapt to environmental dynamics (new buildings, street modifications, trees plantations, new licence-exempt hot spots, etc.). For this purpose, the RRM-E automatically decides to update the frequency planning information. On a fixed period (every week, month, or year, when usual traffic load decreases) requests are transmitted to each radio access points to rescan their surroundings and inform the RRM-E.

Updates can also be done outside those periodic requests if link budget becomes worse for some links. The node can then either change for its alternative channel if one was specified or redo its whole scanning process. New station deployment can also be considered automatically as soon as deployment information is collected by the RRM-E.

6.8 Cognitive Frequency Band Allocation

Cognitive radio based RRM techniques are a feasible approach for system's joint design of access and backhaul. It has been proposed as a potential way to more efficiently utilize radio spectrum. By combining the abilities of spectrum awareness, intelligence and radio flexibility, cognitive radio based approach is able to adapt itself to the changes in the local environment. Compared to conventional dynamic RRM approaches, cognitive radio based techniques have the potential to greatly improve spectrum efficiency, reduce overall complexity, and improve link reliability. A brief introduction on cognitive radio techniques is given first and then the details of cognitive radio based channel assignment for the described system is provided in this clause.

6.8.1 Cognitive Radios

Cognitive Radio based spectrum assignment was first introduced in [i.6]. The inefficient usage of the existing spectrum can be improved through opportunistic access to the licensed bands without interfering with the existing users. The definition of cognitive radio suggested by FCC [i.4] is: '*A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which is operates. This interaction may involve active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio*'. The fundamental objective of cognitive radio is to enable an efficient utilization of the wireless spectrum through a highly reliable approach.

Based on the definition of cognitive radio, two main elements can be outlined: the cognition part and the reconfigurability. By combining these two functions together, cognitive radios are able to access the spectrum in a fully dynamic way. In our system the cognitive radio behaviour is applied in the access and self-backhauling segment, even if the system operation uses licensed bands.

6.8.2 Cognition

Cognition. The cognitive capability is the most distinguishing feature of cognitive radio [i.6], because helps capture the variations of the radio environment over a period of time or space. There three main elements in cognition, spectrum sensing, spectrum analysis and spectrum decision. These functions are the basis of the on-line interaction between cognitive radio and the unpredictable environment. The details of the functions are as follows:

- Spectrum sensing: Cognitive radio scans the available spectrum, estimating the interference level of it. Then cognitive radio detects the interference holes.
- Spectrum analysis: Based on the information provided by spectrum sensing, cognitive radio will estimate the channel state and the channel capacity.
- Spectrum decision: According to the previous information provided by spectrum sensing and spectrum analysis, a cognitive radio needs to determine not only which available channel to use but also the transmission parameters, e.g. the transmission mode, the data rate and transmission power, etc., [i.5].

After the three steps above, cognitive radio will have enough information to adjust its operating parameters to perform the communication. The cognition part is the intelligence intensive part of cognitive radio where different intelligent techniques are applied to, including reasoning and learning.

6.8.3 Reconfiguration

Another important feature of cognitive radio is the capability of adaptation [i.7] and [i.8]. Cognitive radio will adapt its internal states to the variations of the wireless environment by adjust certain operating parameters. There are a few basic operating parameters that can be reconfigured by cognitive radio:

- Carrier frequency: The capability of adjusting the carrier frequency is the fundamental function of cognitive radio. If the current spectrum in use is no longer suitable, cognitive radio needs to move to the most appropriate frequency band according to the spectrum decision made by it.
- Transmission power: Dynamic transmission power control can also be performed in cognitive radio scenario. The appropriate transmission power level will be applied to decrease the interference and allow more users sharing the same spectrum.
- Modulation: Modulation scheme is also reconfigurable. By realizing the characteristics of the targeting spectrum and the environment, cognitive radio is able to select the most suitable modulation to perform the communication.

Cognitive radios operate in a very complex heterogeneous scenario. The online adaptation of the operating parameters provides the basis for cognitive radio to dynamically interact with the environment.

6.8.4 Cognitive Channel Assignment

Cognitive radio channel assignment techniques will be developed for the entities in this system, including both access and self-backhaul networks in principle, in relation to the use of un-licensed spectrum or licensed spectrum designated to its operation. However, cognitive radio based approach is expected to perform better at the HBS - HSS (the HSS is co-located at the ABS) link than the ABS - MS link since the HBSs and ABSs (HSSs) are all spatially fixed and hence more stable. The situation for the access network is different because of the mobility of MSs. The highly dynamic nature of access network calls for highly efficient learning algorithms.

The cognitive radio based approach for our system can be briefly illustrated by figure 6.14. There are mainly three steps in the communication process: Frequency Awareness, Frequency Resource Management and Action. After receiving a transmission request, the operating cognitive radio based base station/mobile user will firstly obtain the information of frequency availability either by monitoring channel utilization database or through spectrum sensing. Then a decision is made at the frequency resource management part. An intelligent frequency decision making process is enabled through learning and reasoning. After that, the system will adapt some of the parameters and then start to transmit data.

6.8.4.1 Frequency Awareness

Frequency Awareness is an essential part of cognitive radio based RRM techniques. The characteristics of frequency channels and the availability of spectrum are captured in the frequency awareness process. Cognitive radio based channel assignment is then carried out based on the information obtained by the frequency awareness. A certain level of awareness of the frequency environment is required in our system in order to carry out cognitive radio based channel assignment.

A low complexity spectrum sensing approach or a channel usage database is suggested, for actually performing the frequency awareness process. Information of spectrum utilization is obtained either through a database or spectrum sensing. Perfect sensing may not desirable, since there are still challenges in developing perfect spectrum sensing techniques, and such challenges may keep perfect sensing techniques years away from implementation. Limited sensing capability has the potential to deliver much of the required performance by combining with other advanced techniques, like learning.

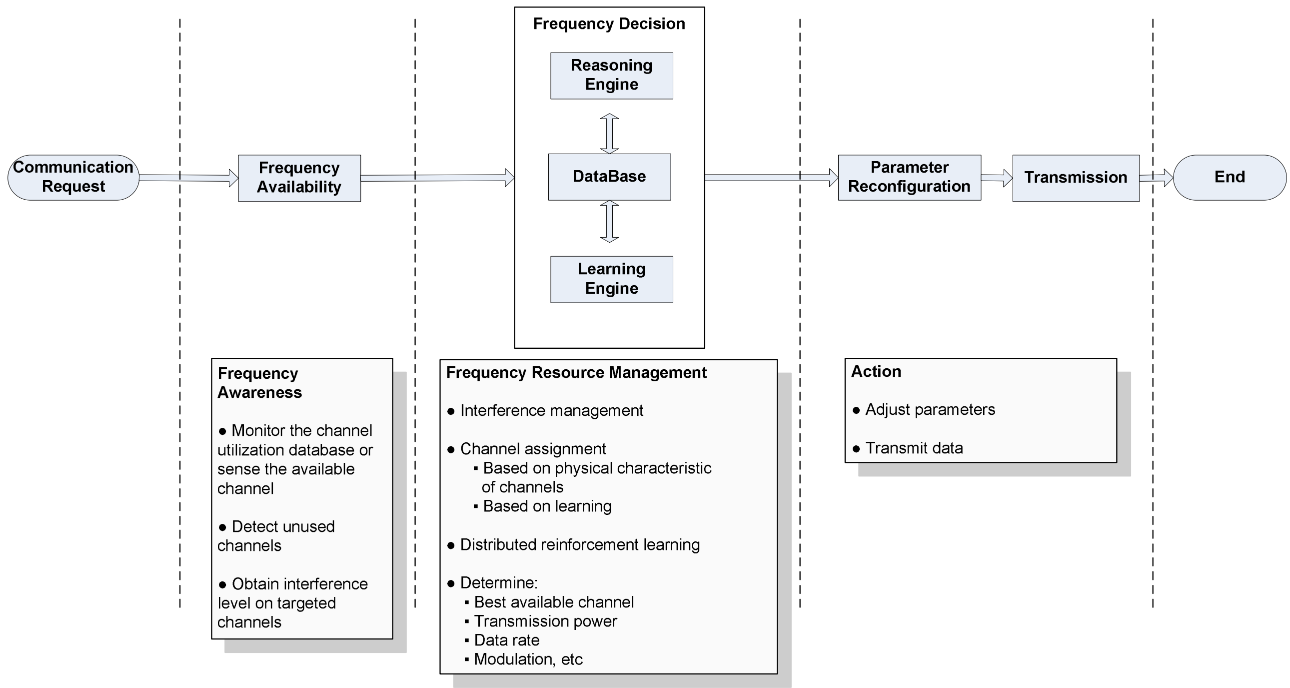


Figure 6.14: Cognitive radio based RRM

6.8.4.2 Channel Assignment

A reinforcement learning based cognitive radio channel assignment approach is required for our system. This approach will be used as a starting point to address the channel assignment issue. Reinforcement learning [i.8] is a machine learning approach where an agent learns from trial-and-error interactions with an unknown environment. It can be configured in a distributed way, where the learning depends only on localized information. Therefore, reinforcement learning is perfectly suited to distributed decision making.

A possible channel assignment algorithm is shown in figure 6.15. As we mentioned previously, this algorithm will be applied initially to both access and self-backhaul networks of our system. During operation a more sophisticated approach can be developed based on more feedback obtained from the simulation. Channels are allocated based on the level of interference on channels and the experience gained through learning. We consider E_i is entity i in our system. E_i is element of E and E is the entity set that contains all reinforcement learning based BS and MS. By randomly choosing channels, the operating entity E_i will explore the spectrum space first. After a number of used channels have been discovered, the user will then exploit high weight channels with a higher priority.

By using reinforcement-based learning, entities in the system will assess the success level of a particular action. This in our scenario is whether the target channel is suitable for the considered communication request. According to the previous judgments, a reward is assigned in order to reinforce the weight of the physical resource. The concept of 'weight' is a number assigned to a resource, and the number reflects the importance of the resource to a certain entity. Entities select channels to use based on the weights assigned to the spectral resources - resources with higher weights are considered higher priority.

A key element of reinforcement learning is the value function. A learning based entity updates its knowledge based on the feedback of the reward function. The following linear function is proposed, as the value function to update the knowledge base:

$$W' = f_1 W + f_2 \qquad (1)$$

where W is the weight of a channel at time $t-1$, and W' is the weight at time t according to previous weight W and the updated feedback from system. f_1 and f_2 are the weighting factors at time t that will take on different values depending on the localized judgment of current system states and the environment. Table 6.1 shows the values of f_1 and f_2 that will be initially used for our system.

Table 6.1: Weighting Factor Values

f_1		f_2	
Reward	Punishment	Reward	Punishment
1	1	1	-1

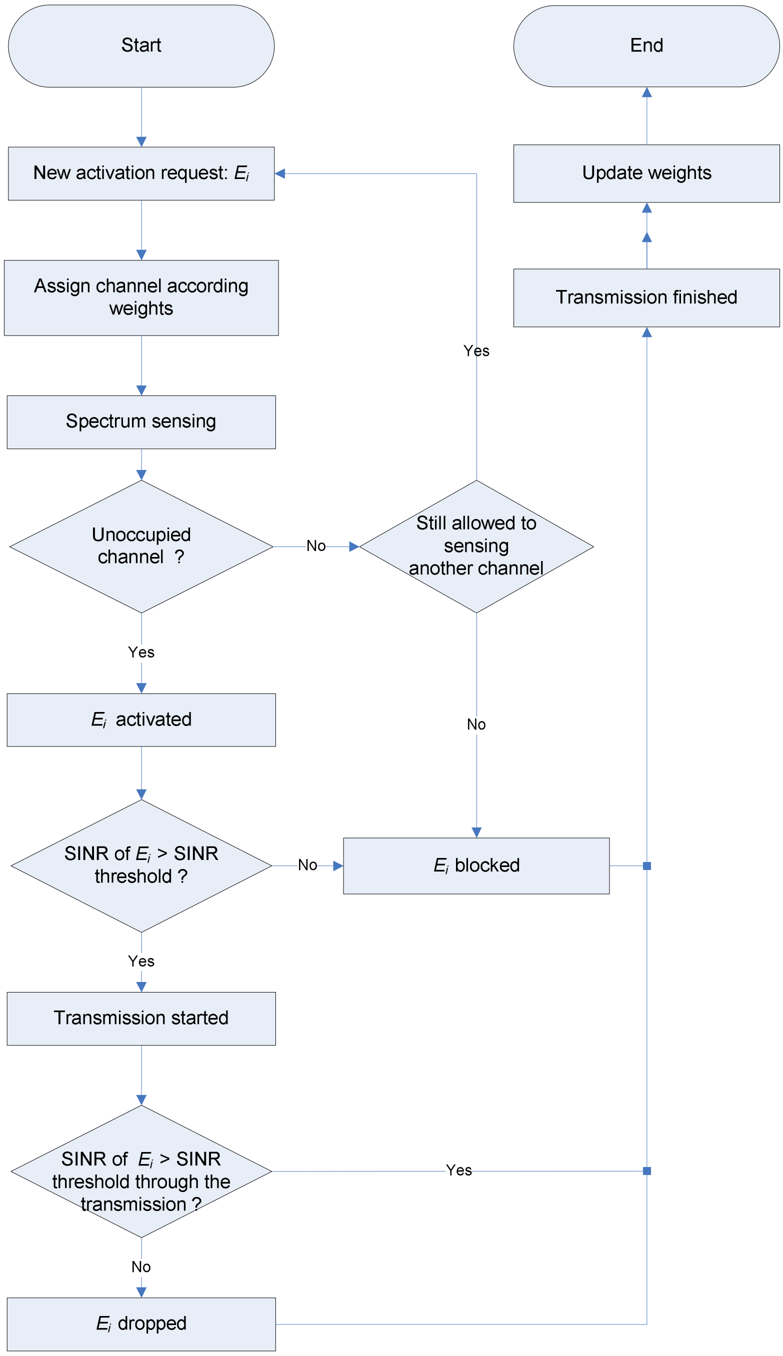


Figure 6.15: Reinforcement learning based channel assignment algorithm

6.8.5 Application of Algorithm

The algorithm described above will be used as a baseline algorithm for both access and self-backhaul networks. Channel assignment will be carried out in two scenarios: licensed band only and licensed band plus unlicensed band. The learning based algorithm is expected to be more effective in channel assignment at HBS/ABS since the base stations are spatially fixed, meaning that the environment is less dynamic. Appropriate improvement will be made to achieve better spectrum efficiency according to the feedbacks from simulation.

Learning efficiency is crucial when applying reinforcement learning to our system, since learning entities will cause a higher level of disturbance in the exploration phase. Since the algorithm is designed to work in a distributed fashion, such that entities depend only on localized information, one of the potential drawback of the distributed system is the convergence process can be very slow. One possible solution to overcome this problem is to apply *Docition* based techniques. By allowing neighbouring entities to exchange learning based information at the minimum level, docitive approaches are proven to be significantly effective in reducing convergence time. The weight of used channels, in this scenario, is one of the possible items of information to be exchanged between entities. The learning enabled channel partitioning is expected to be very quick in this case, and the convergence of learning based entities has the potential to be significantly improved.

Efficient exploration techniques may also desirable in order to improve the learning efficiency, particularly for the more dynamic access networks. Two completely opposing tasks need to be combined if an agent wants to find its optimal action strategies to intelligently interact with a dynamic environment. To obtain enough knowledge to distinguish between the excellent and poor actions, an agent needs to repeat previous actions. However, to discover such actions, a learning agent has to try as many different actions as possible. Neither exploration nor exploitation can be performed exclusively in learning. The learning process cannot be considered as efficient if information gained through exploitation is not used in exploration. This inherent tradeoff in reinforcement learning also has a significant influence on cognitive radio in terms of system performance. Our system will receive more interruptions, caused by the hidden terminal effect, in the exploration stage. Most of the existing reinforcement learning based algorithms apply a random exploration strategy with uniform probability, like 'uniform random walk'. Research shows that the uniform random exploration is the most inefficient approach to achieve a goal. One of the efficient exploration techniques developed, for example, is weight-driven exploration. The exploitation phase is gradually moved into exploration by applying a weight-driven probability distribution to influence action selection during exploration. Thus, exploration will be more efficient and the overall performance of the cognitive radio system can be improved. Efficient exploration techniques will be developed and tailored for the system, and will be reported in the subsequent deliverable.

When applying this approach in the licensed bands, a problem is that no feedback can be provided initially at the installation of the access network, due to lack of mobile subscribers. In the case of the backhaul network beacon messages from start-up HSSs may be included. However, HBSs may not hear the ABSs, due to their lack of traffic or "hidden" transmissions. In order to prevent HBSs from initially occupying all the available frequency channels, it may be necessary to obtain information about ABSs in the local area from a database.

6.9 Time Resource Allocation

6.9.1 Spectrum Sharing between Access and Hub Wireless Networks

This system is targeting an aggressive frequency reuse between access and backhaul networks. However the performance of the system with an aggressive frequency reuse may be limited by interference; and techniques for separating the interference in frequency domain or in time domain can be used.

6.9.1.1 Frame Structures for Spectrum Sharing in Time Domain

The solution for sharing a frequency channel between access and self-backhauling may fully separate the time used by the backhaul from the time used by the access. This condition will be named in continuation as Reuse ½, as each system will use ½ of the time resource. Type 1 frame structure presented below reflects this approach.

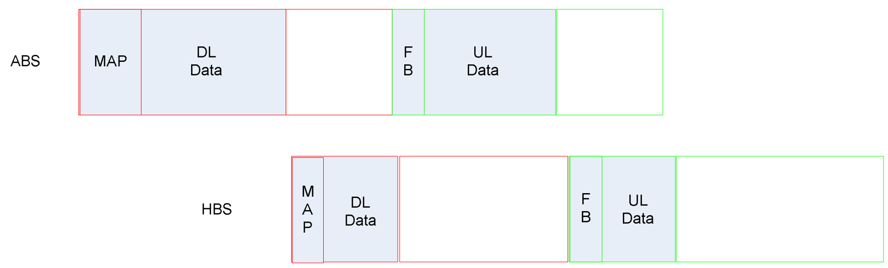


Figure 6.16: Frame structure type 1

This frame structure resolves the co-location problem by avoiding simultaneous transmissions and receptions at ABS location.

The major disadvantages are:

- Operation in Reuse 1 is not possible, due to the collocation problem.
- The DL interval per system is limited to approximately ½ of the DL sub-frame.
- The UL interval per system is limited to approximately ½ of the UL sub-frame, having as practical effect the limitation of the UL cell size at half of the cell size of the regular access system.

In case of insignificant interference, the full spectrum should be used by both the access and the backhauling system. This condition will be named in continuation Reuse 1, as each system may use the entire part of the time resource. Type 2 frame reflects this approach.

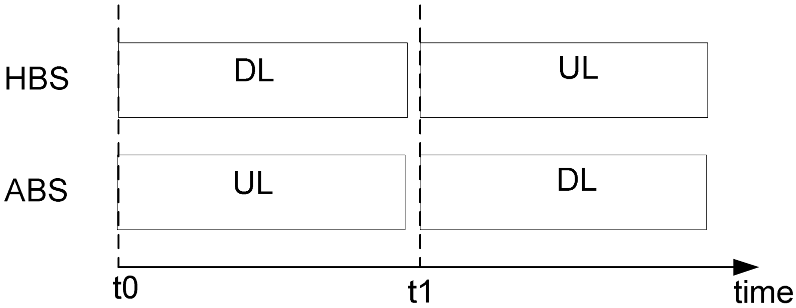


Figure 6.17: Frame structure type 2

This frame structure allows the full usage of the frequency channel and the full range of the access cell. However, if there is a need to separate some interference between the hub and access system, the frame needs a modification.

A novel frame structure (Type 3) is presented below. Due to its adaptation to different scenarios, this frame structure is a good candidate for being used in SON protocols.

This frame structure, aligned with the ABS downlink transmission, natively supports the collocation of ABS and HSS. At ABS/HSS location there is either only ABS/HSS transmission or reception.

The access and self-backhauling traffic can be scheduled at ABS/HSS location according to the following reuse schemes:

- Reuse 1, both ABS and HSS are transmitting OR receiving in the same time.
- Reuse ½, ABS and HSS are NOT transmitting OR receiving in the same time.

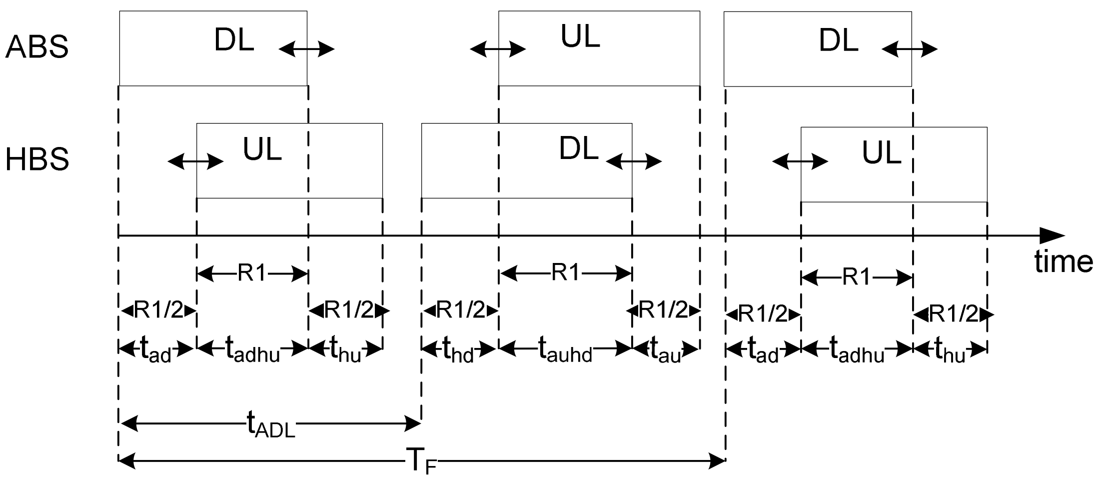


Figure 6.18: Frame structure type 3

6.9.1.1.1 Frame Structure Elements for SON Support

The duration of the ABS frame is fixed and noted with T_F. The duration of the downlink (t_{ADL}) and up-link ABS sub-frames may be changed as function of the rapport between the DL and UL traffic; however such change will affect the interference in the access network and it is in general not recommended.

The duration of the different reuse schemes can be adjusted, as indicated by the horizontal arrows in figure 6.18.

The durations of interest are:

t_{ad} - duration of ABS DL transmission in Reuse ½;

t_{adhu} - duration of ABS DL transmission and simultaneous HSS UL transmission (Reuse 1);

t_{hu} - duration of HSS UL transmission in Reuse ½;

t_{hd} - duration of HSS reception (HBS DL transmission) in Reuse ½;

t_{auhd} - duration of ABS reception and simultaneous HBS DL transmission (HSS reception) (Reuse 1);

t_{au} - duration of ABS reception in Reuse ½;

t_{ADL} - maximum possible duration for ABS downlink sub-frame.

The SON algorithms to be defined are expected to tune the optimum durations for the above variables, such to locally and generally maximize the capacity of the system. The resolution for changing these variables depends of the actual technology used by the access and self-backhaul network.

6.10 RRM for joint access and self-backhaul networks

This clause deals with radio resource management procedures, mainly power allocation, with the aim to facilitate the capacity needs of our system. In here, we mainly consider a single-frequency network for both access and self-backhaul links; performance is expected to improve if more than one backhaul interface is available. Due to the sheer size of a high-capacity network, our main approach is along cognitive mechanisms. These are known to allow for autonomous operation, and are thus an important step towards the SON operability needed within the system.

6.10.1 Cognitive and Docitive RRM

Subsequently, we introduce the known cognitive and the innovative docitive approach in dealing with the complex task of assigning radio resources in our system high-density network.

6.10.1.1 Problem Statement

The starting point for our investigations is the architecture depicted in figure 6.20, where an HBS serves several below-rooftop ABSs which in turn serve associated MSs. The aim is to design an architecture which is cost efficient whilst providing a capacity density of 1 Gbit/s/km^2. To facilitate this goal to be achieved, our system will utilize the same spectral bands for both access and some backhaul links. However, whilst the architectural building blocks are available, some serious challenges remain to be addressed and thus constitute the prime focus of our system:

1) The existing 3GPP and IEEE standards for relays allow only time-division relaying, i.e. the HBS first needs to communicate to the ABSs and only then can the ABSs communicate to the MSs. The spectral efficiency is thus roughly halved. A more aggressive approach would be to allow both backhaul as well as access links to communicate simultaneously. This, however, constitutes a serious challenge in interference management, i.e. interference avoidance, mitigation and suppression.

2) The complexity of the complete system at hand is very large. Notably, the system to be optimized will be composed of at least one HBS, several decentralized ABSs and a fairly large amount of MSs. In addition, the optimization scope will include the operation over license and license-exempt bands, presenting different interference conditions. If the optimization problem can be formalised, it is likely to be NP-complete and/or non-convex and thus a solution eludes the majority of tools available to date dealing with system optimization.

3) The system as a whole is highly dynamic, likely to yield non-stationary effects in both observation as well as actions to be taken by the involved parties. This means that the system should be sufficiently adaptive and self-organizing in the sense that changes in the operational conditions should be handled well by the system. Another implication is that most theoretical toolboxes break down and more computerized solving methods, such as machine learning, have to be invoked to yield viable results. The prime problem here is that most machine learning approaches assume perfect knowledge of the entire system and coordination between the involved parties.

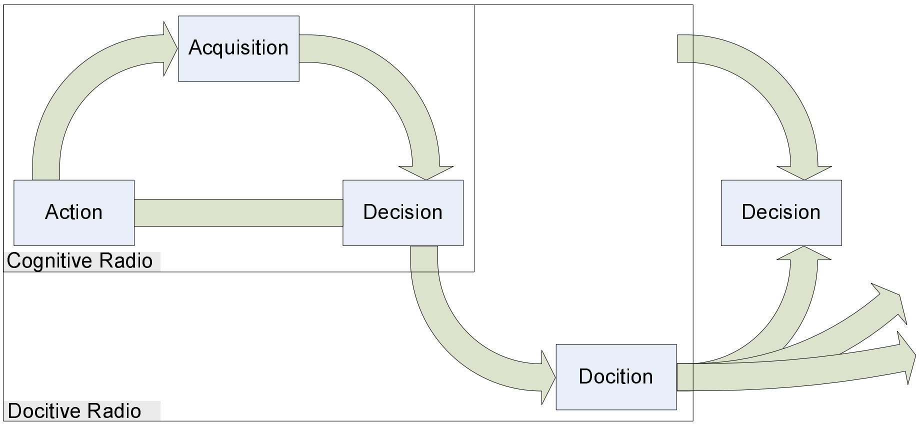


Figure 6.19: Canonical cognitive cycle and its extension through docition

1) One of the grandest challenges in autonomous systems is the speed and accuracy of convergence of the decision-taking algorithms to the prior set targets. Indeed, the first contributions in this area in the context of wireless communication systems often require several tens of thousands of iterations before converging within tolerable limits. Depending on the algorithm of choice, another challenge is to ensure that the information exchanged between learning nodes is kept to a minimum. Inspired by these shortcomings, [i.9], [i.10] and subsequent citations, [i.11], [i.12] and [i.13] have independently introduced a framework where network entities with greater experience share their knowledge with entities of lesser experience.

2) The latter introduces more broadly the emerging framework of docitive radios, from "docere" = "to teach" in Latin, which relates to networking entities which teach other entities. These entities are not (only) supposed to teach end-results (e.g. in form of "I sense the spectrum to be occupied"), but rather elements of the methods of getting there. This concept mimics well our society-driven pupil-teacher paradigm which generally acknowledges that inferior teachers teach end-result whereas good teachers facilitate learning.

3) As illustrated in figure 6.19, the canonical autonomous decision-taking cycle is advantageously extended by the element of docition, which is realized by means of an entity which facilitates knowledge dissemination and propagation with the non-trivial aim to facilitate learning. Translated back to the wireless setting, this implies a distributed and autonomous approach where nodes share potentially differing amounts of intelligence/expertness acquired on the run. This, in turn, is expected to sharpen and speed up the learning process.

4) Our prime aim is to utilize this docitive framework in the context of joint access and backhaul design. Here, interference is created between the backhaul links (HBS-ABSs) and access links (ABSs-MSs), which requires intelligent RRM policies at both HBS as well as ABSs. We will commence our investigations assuming a fixed transmission strategy at the HBS and a docitive framework at the ABSs. At a later stage, we will also aim to improve the performance by allowing the HBS to be governed by docitive mechanisms.

5) Numerous interesting problems emerge across various communities in the context of docitive radios. For instance, from an information theoretical point of view, one of the core problems is how to quantify the degree of intelligence of a cognitive algorithm. With this information at hand, intelligence gradients can be established where docition should primarily happen along the strongest gradient. This would also allow one to quantify the tradeoff between providing docitive information versus the cost to deliver it via the wireless interface. Some other pertinent questions encompassing also the physical and medium access control layers are how much information should be taught, can it be encoded such that learning radios with differing degrees of intelligence can profit from a single multicast transmission, how much feedback is needed, how often should be taught, etc.? We believe that we have just touched upon the tip of an iceberg as preliminary investigations have shown that docitive networks are a true facilitator for the utmost efficiency in management and utilization of scarce spectral resources and thus an enabler for emerging as well as unprecedented wireless applications.

6) We note that the system architecture will enable the exchange of information between ABSs via the HBS central node and will facilitate the centralized decision by an intelligent entity located at the HBS. For reducing the decision time, policy rules may be implemented by ABSs. The actions may be also related to emulation of situations allowing the assessments of interference created by specific transmitters.

6.10.2 System-Wide Simulation Results

In this clause, we analyze the system-wide simulation results obtained from the simulations. The simulation details can be found in [i.15] and [i.16].

In the following clauses we show the simulation results for different experiments. We analyze the architecture and cognitive algorithm solution proposed. Simulation results show the total capacity achieved by the joint access-backhaul link design proposed.

We focused on a single beam, that consists of one HBS (shared by all the beams) and four ABSs, placed in a 2 by 2 matrix form. The separation between ABSs is 100 m, and the HBS is located 350 m away from the ABS distribution centre. We consider one MS for each ABSs, which is randomly located within a 75 m radius coverage of each ABSs. For the whole system we consider that the different ABSs distributions are located equidistantly from the HBS forming a circumference. The distance between the centre of a distribution and the two adjacent ones is 350 m. We further assume that the coverage area of an ABS distribution is circular with radius 145 m and hence a surface of 0,67 km^2 which is a bit larger than the real one.

The simulation results for 50 trials show that on average the spectrum required to achieve 1 Gbit/s is 15,1 MHz (see figure 6.22); with this spectrum the total capacity achieved by the HBS is 4 Gbit/s (all beams). The mean spectral efficiency of the sum access link (ABS to the MSs) is 5,1 bit/s/Hz and the mean backhaul spectral efficiency is 5,4 bit/s/Hz. Figure 6.18 shows the capacity in bit/s/Hz of the access link and the backhaul link. In figure 6.23 the total capacity for a HBS is shown when using a bandwidth of 40 MHz. Likewise, figure 6.24 shows the capacity density in terms of Gbit/s/km^2 when using an allocation bandwidth of 40 MHz.

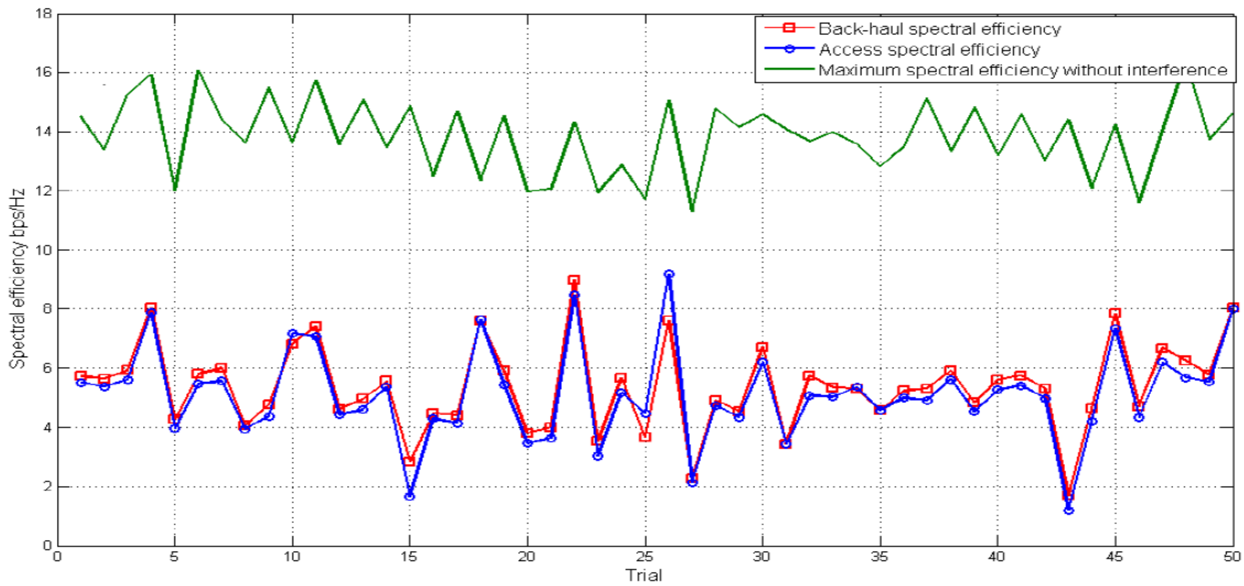


Figure 6.20: Spectral efficiency of the system in bit/s/Hz

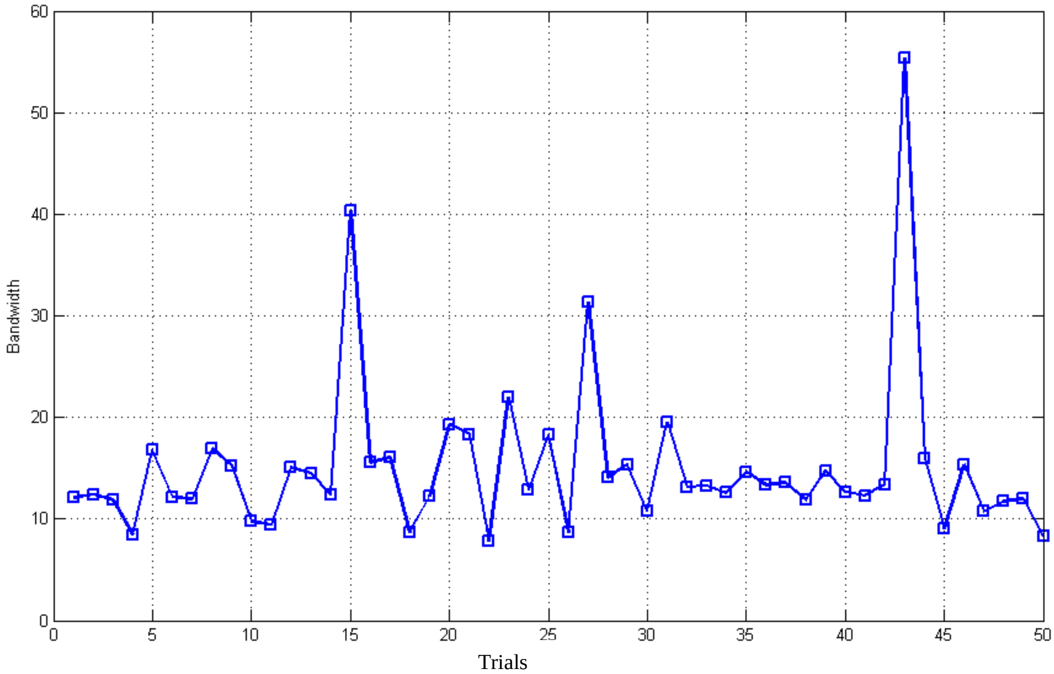


Figure 6.21: Bandwidth (MHz) required to achieve 1Gbit/s/km^2

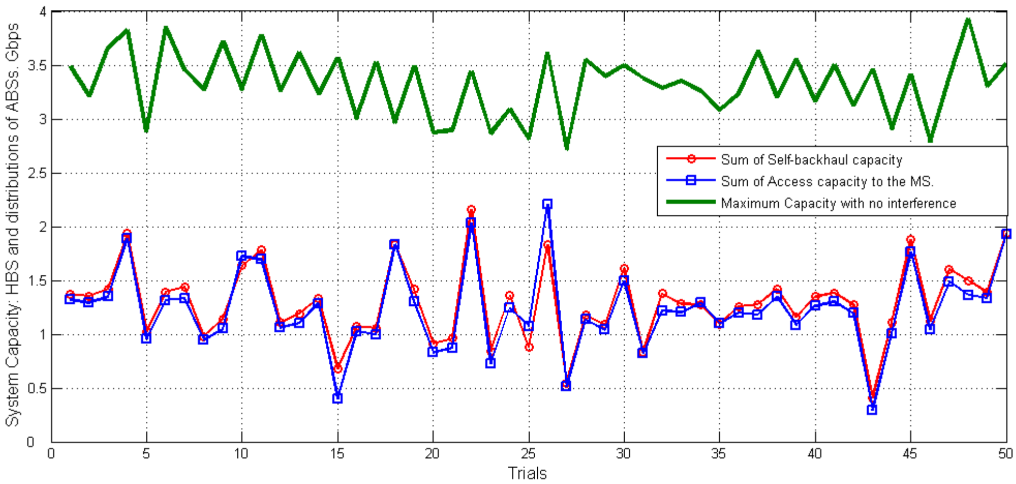


Figure 6.22: System capacity assuming a bandwidth of 40 MHz

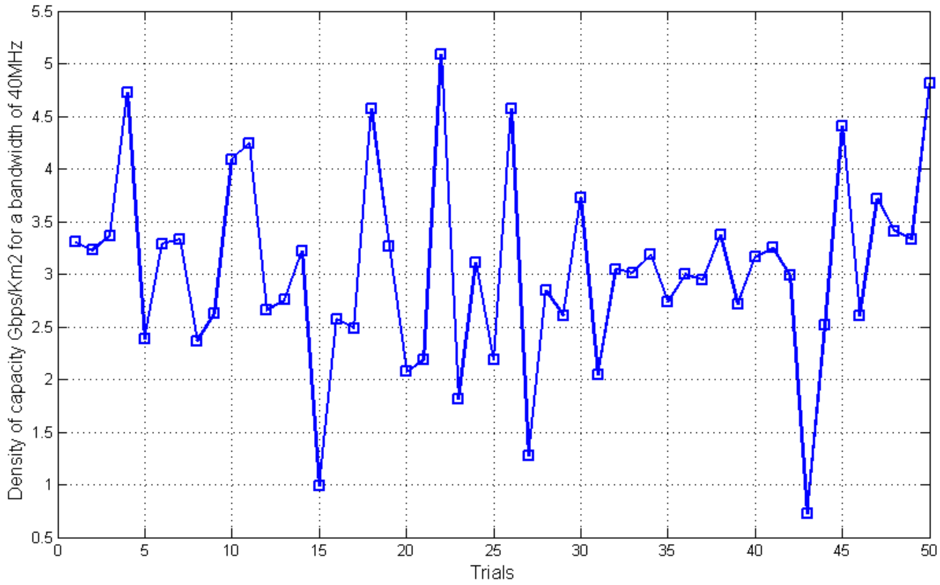


Figure 6.23: Total capacity density (Gbit/s/km^2) of the system for 40 MHz bandwidth

6.11 Direct Communication

The direct communication between the entities of the radio network takes place over the air, involving functions at both lower and higher layers.

In the next clauses is defined the direct communication mode at the lower resource levels and are given a number of examples for frame structures and resource block partitions.

We define two types of Direct Communication Operation (DCO) between system's entities, preferably within the licensed spectrum:

- DCO between Base Stations.
- DCO between subscriber stations (MS or HSS). An HSS is a station connected to HBS and collocated with an ABS.

In continuation are presented possible frame structures and the frequency resource allocation, such to enable the channel utilization by multiple communications.

6.11.1 Time-domain Frame Structures

6.11.1.1 DCO in the ABS and HBS Radio Frame

The ADC (ABS DCO) and HDC (HBS DCO) may be split in BS-BS communication and MS-MS communication and can be aligned as shown in figure 6.24. The BS-BS communication is part of the DL subframe and the MS-MS communication is part of the uplink subframe, such that adding interference between ABS and HBS cells is avoided. The BS DCO is naturally placed at the end of the DL subframe, while the MS DCO can be placed either at the beginning (figure 6.24) or at the end of the UL subframe (figure 6.26). The HBS DL and UL sub-frames may be shorter, if it is required to separate the interference created to an MS in the ABS cell.

The interference may be created by a transmitting entity to a receiving entity, placed in the proximity of the transmitting entity. In order to avoid such situation, the DCO zones within HDC and ABS time-domain partitions should be synchronized across the wireless network.

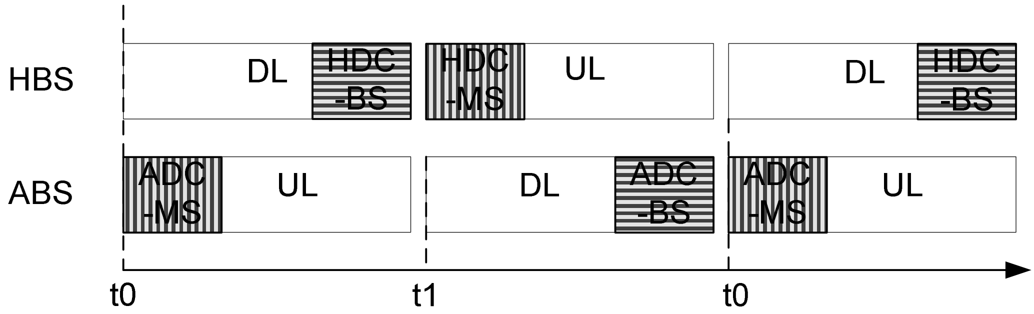


Figure 6.24: Not-aligned P-MP and DCO in HBS and ABS cells

The variant in figure 6.26 brings us to an interesting outcome: the access and the DCO are separated in the time domain across the network, because the same time partition for DCO or for regular cellular operation is being used in both ABS and HBS cells.

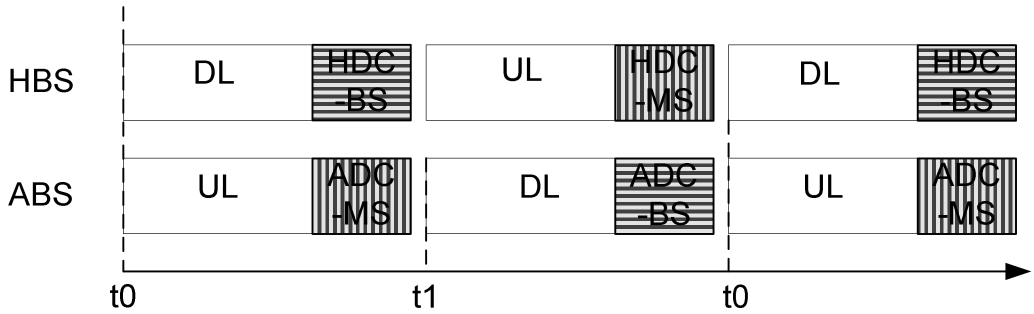


Figure 6.25: Aligned P-MP and DCO in HBS and ABS cells

6.11.2 Assignment of Frequency and Time Resources

The basic principles which are used for the assignment of resources for DCO are listed below. These principles are general, being independent of the system architecture.

1) The DCO uses a resource allocation, defined as combined time resource and frequency resource within a frequency channel.
2) The direct communication inside the BS cell should not affect the start of DL frame and the transmission of the preambles and control channels or synchronization signals.
3) The protocol used for direct communication may be a derivation of the used cellular protocol or may be a different protocol.
4) A BS may hop to another frequency for the duration of the DCO and on this frequency the BS may use a different air protocol as compared with the protocol used in cellular communication.
5) An MS/SS can transmit to another MS during the radio frame, while respecting the restrictions above. In FDD, the MS transmission may be done on either DL or UL frequencies.
6) A BS may transmit to another BS either during the DL or UL subframes (TDD) or using either DL or UL frequencies (FDD).
7) A BS may hop to another frequency for the duration of the DCO.
8) The direct communication mode may use a pre-scheduled time and/or frequency resource, dedicated to such communications only or the frequency channel may be used for DCO and regular communications.

9) If the time resource is dedicated for DCO only (Mode 1), the resource can be used by multiple communication groups, the sharing being done in the frequency domain, the time domain or a combination of both. A communication group is constituted by those radio units which directly communicate one with each other.

A time resource can be one or more:

- TTI intervals.
- DL or UL slots or sub-frames.
- Sub-frames or slots.

A frequency resource may be composed of:

- a number of sub-channels; or
- a number of resource blocks.

A communication group can include two or more BS entities or two or more MS/SS entities.

10) If the time and frequency resources are used for both DCO and regular operation (Mode 2), there may be allocated a number of resources for DCO only, and other resources can be either used for regular cellular operation only or may be used for a combination of DCO and regular cellular operation.

11) If a BS is transmitting during the UL, it should operate as an MS. If an MS is transmitting during the DL, it should use the allocated frequency resource like a BS.

12) An entity can use, when transmitting, a mode which is different from the mode used by the pair entity for regular cellular reception.

6.12 Out-of-band self backhauling

6.12.1 Capacity and Spectrum Calculation in 5 GHz

The spectrum in 5 GHz is mainly needed in a scenario where ABS uses only one frequency channel per direction.

Given the un-licensed usage of 5 GHz band, we will assume a limitation to 16QAM3/4, even if the S/I is 30 dB. The channel size is 20 MHz. The radar detection requirement will impose an additional 20 % loss. The resulting data traffic is 22,4 Mbit/s/channel - therefore a 60 MHz of spectrum is required to achieve 65 Mbit/s. Note that based on the regulatory occupancy rules, the 60 MHz can be placed at different frequencies in the different sectors.

6.12.2 Backhaul Capacity at 60 GHz

This clause examines the capacity of a backhaul system at 60 GHz for the HBS/ABS rollout scenario currently suggested for the project. The analysis checks several possible frequency usage schemes and calculates the interference limited rate. A calculation is done for two cases:

- A theoretical case demonstrating 60 GHz band capabilities.
- A practical case, demonstrating the expected 60 GHz equipment capabilities.

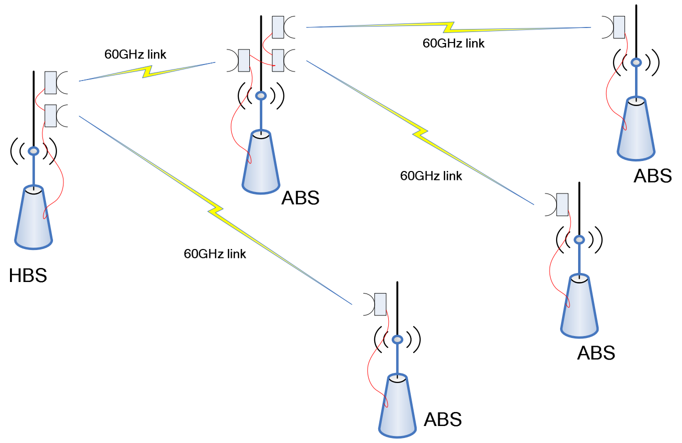


Figure 6.26: Typical backhaul system architecture (tree)

The 60 GHz backhaul system can be viewed as a wireless Insert-Drop Multiplexer or a wireless Ethernet switch. The system is intended to provide immediate access to the wireless BS using the 60 GHz band, which does not require licensing or coordination between operating devices because of the characteristic natural directivity and considerable propagation loss. The 60 GHz backhaul link supports multiple wireless hops by virtue of its insert-drop capability. Since each end point of a wireless backhaul link behaves as a Ethernet switch (with one port being wireless), each end-point may locally generate some data, and also forward the data arriving from a peer point-to-point link (typically pointing in a different direction). The backhaul system is typically used a tree architecture (shown in the drawing below), but it may also be used in a ring or mesh architecture. In the drawing, note the wired Ethernet connections, one for each BS location (marked by red lines), which may be located right on the antenna mast, thus yielding a very compact, low footprint backhaul connection.

6.12.2.1 Rollout Scenario

The analysis focuses on two frequency usage schemes. In one scheme only one frequency channel is allocated in the entire 60 GHz spectrum (which may then utilize the entire available spectrum). The other scheme assumes two frequency channels (in which case each channel can only use half of the available channel). The object of this allocation is to demonstrate the enormous capacity available in the 60 GHz band, which in practice is quite tolerant to interference. In fact, the situation analyzed demonstrates a type of worst case scenario, in which neighbouring ABSs are subject to the strongest possible interference, as the assumption of completely straight streets prevents the spatial filtering gain naturally available at 60 GHz when dealing with more 'natural' rollouts (i.e. not on a mathematical grid).

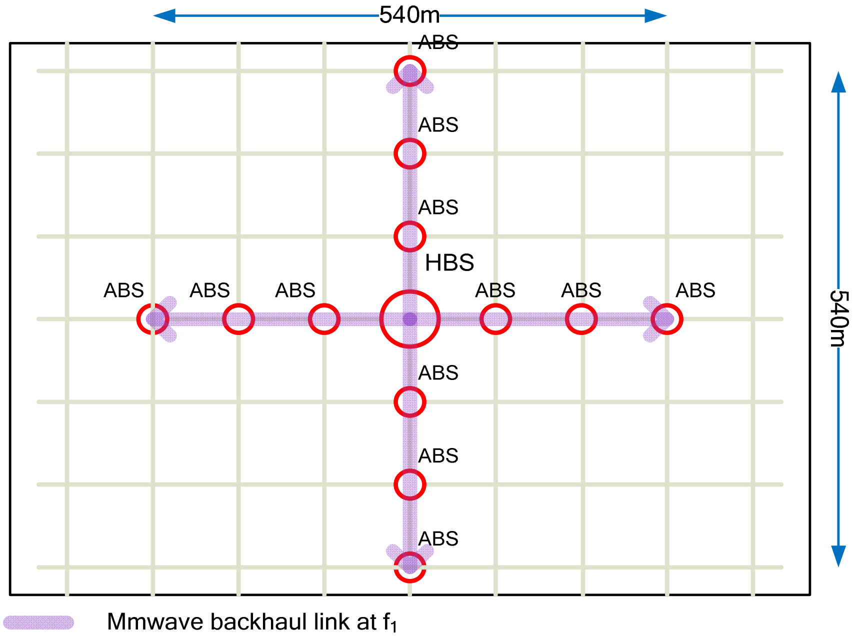


Figure 6.27: Backhaul rollout scenario using one frequency

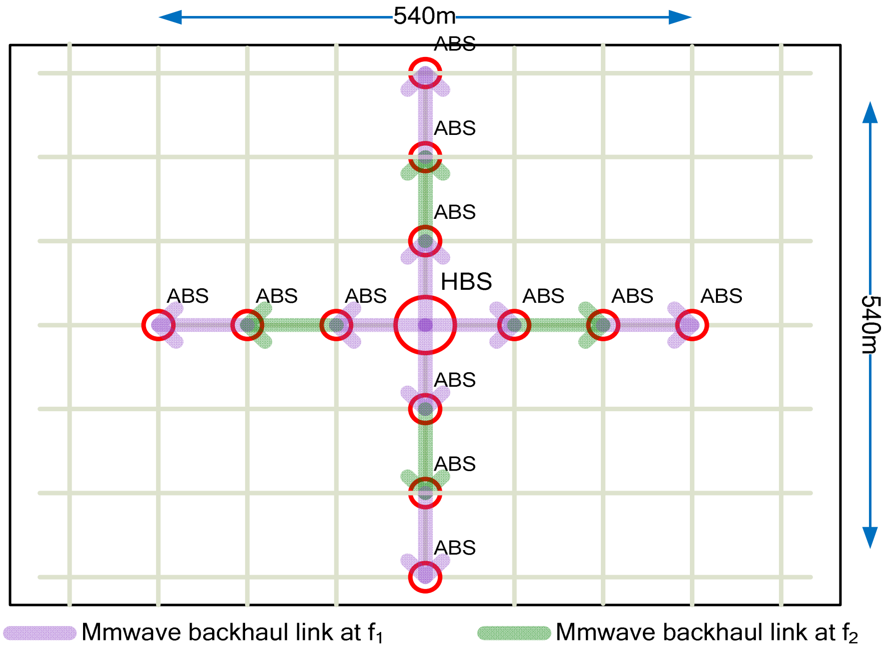


Figure 6.28: Backhaul rollout scenario using two frequencies

The analysis of the rollout plan above reveals that the 60 GHz backhaul link is constrained to follow the streets canyons. The reason for this constraint is that the Point-to-Point (P2P) links at 60 GHz require a clear line of sight for their operation. The ABS, to which the P2P link should connect, is located **below** the roof-top level. Additionally we assume that in the interest of compactness, and low-cost for the overall installation, the P2P link and the ABS are collocated, possibly even within the same enclosure. As a result of these constraints, the P2P link (at least one side of it) will be located below the roof-top level, regardless of whether the HBS is located above or below the street level.

Another observation that can be made is that there are two possibilities to connect the backhaul links:

- Direct connect - Each ABS has a direct link to the HBS. In this case all the links support the same data-rate, but have a different link distance.

- Daisy chain - Each ABS connects to the next ABS and the ABS closest to the HBS connects the entire chain to the HBS. In this case the links carry different data rates, but all have the same link distance.

In general the daisy-chain connection outperforms the direct connect approach, and offers much more in ways of network survivability and flexibility, which is why the drawings above demonstrate this method, and the calculations done later relate to it.

6.12.2.2 Backhaul Data Rate Calculations

The calculations on the 60 GHz backhaul data rate are based on several assumptions, which will be detailed below:

- Small print-foot antenna is used - This size of antenna is compact yet provides considerable gain. A different trade off between gain and size could be considered - based on the maximum required distance, reliability requirements, and worst case rain conditions.

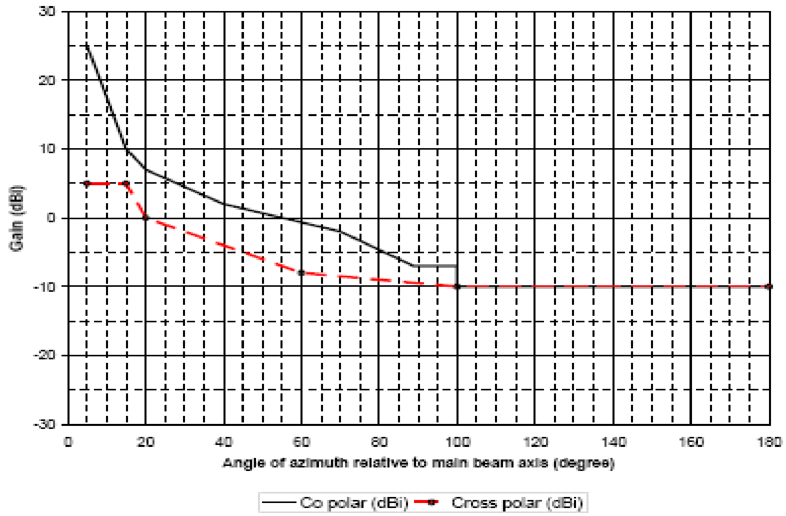
- Free-space loss and oxygen loss are accounted in the link budget. Free space loss is present in any wireless system. Oxygen loss is a special feature of the 60 GHz frequency band, and is caused by absorption of the electromagnetic radiation by the oxygen molecules in the atmosphere. This loss is quite high, and amounts to almost 16 dB per km of link distance at the sea level.

- Rain attenuation is accounted in the link budget - Rain is also a loss factor at mm-wave frequencies. The absorption by rain is characterized by a figure in dB per km, similar to the Oxygen case, but the loss depends on the rate of fall of the rain. The calculation is done for a specific rain level, which is characterized by measurements to be present no more than a certain percentage of the time. Typical percentage range from 0,1 % to 0,001 % to ensure availabilities ranging from 99,9 % up to 99,999 %.

- Modem using Clear timer on compare (CTC) with implementation loss of 2 dB. We assume a typical modern modem implementation.

- Modem efficiency is 70 %. Modem efficiency takes in account those factors that are less obvious than modulation levels and coding rate (e.g. preambles, pilots, overheads) in order to provide a true picture and the payload carrying capabilities of the modem.

The details of the antenna used for the calculation are shown below in terms of Radiation Pattern Envelope (RPE). The antenna has a gain of 41 dB, and a directivity of about 1,2 degrees. This enormous spatial interference rejection capability is actually not fully taken advantage of due to the precise geometrical rollout scenario, as mentioned earlier. This implies that in more natural rollout scenarios higher capacities can be achieved.



Angle (°)	Co-polar (dBi)	Angle (°)	Cross-polar (dBi)
5	25	5	5
15	10	15	5
20	7	20	0
40	2	60	-8
70	-2	100	-10
88,75	-7	180	-10
100	-7		
100	-10		
180	-10		

Figure 6.29: 60 GHz antenna RPE data

6.12.2.3 Theoretical Scenario Analysis

The theoretical scenario assumes that target of the backhaul P2P link is to provide the highest possible capacity utilizing the 60 GHz spectrum. Based on this target, cost considerations of the system are relaxed, while performance considerations are stressed.

The following assumptions have been made:

- All of the 60 GHz spectrum (59 GHz to 64 GHz) is available for the backhaul link - Being license free, widely available and using very directive antennas this assumption is believed to be reasonable.
- A backhaul P2P link can occupy any channel BW up to the full 5 GHz.
- The modem is capable of operation up to 64QAM ½ rate - This type of performance puts only moderate constraint on the cost of the modem and radio working in LOS channel conditions.
- Cross polarization is in use (XPIC) - Cross polarization is a very cheap means to utilize the independence between orthogonal polarization in a LOS propagation scenario to double the available channel BW.
- TX power is 5 dBm - This is a moderate constraint on the 60 GHz radio.
- Receiver NF is 9 dBm - This is a moderate constraint on the 60 GHz radio.

6.12.2.4 Practical Scenario Analysis

The practical scenario assumes that target of the backhaul P2P link is to provide a low cost solution with adequate capacity from utilizing the 60 GHz spectrum. Based on this target, cost considerations of the system are stressed, while performance considerations are relaxed.

The following assumptions have been made:

- A backhaul P2P link can occupy any channel BW of 250 MHz - Considerable reduction to the price of digital interfaces, processors, etc.

- The modem is capable of operation up to 16QAM ½ rate - Reduces to requirements from the radio and hence its cost.
- Cross polarization is NOT in use - Reduce the complexity of the antenna and signal processing chain, and hence their cost.
- TX power is -5 dBm - This is a very modest constraint on the 60 GHz radio.
- Receiver NF is 20 dBm - This is a very modest constraint on the 60 GHz radio.

6.12.2.5 Calculation Details

The path loss formula is taken from [i.14]:

$$92.45 + 20 * \mathrm{LOG}_{10}(\mathrm{f}_{\mathrm{GHz}}) + \mathrm{Att}_{\mathrm{atmosphere}} \times D_{km} + \mathrm{Att}_{\mathrm{rain}} * \frac{D_{km}}{1 + D_{km}/d_0} + 20 * \mathrm{LOG}_{10}(\mathrm{D}_{\mathrm{km}})$$

where Att represents attenuation and D represents distance.

The path loss is composed of free-space loss, atmospheric loss (Oxygen) and rain loss (depends on rain rate). We assume no rain for the capacity calculations, which is the worst case scenario. We assume the presence of rain for link budget calculation, which is again the worst case scenario. The rain attenuation calculation assumes rain zone K, which represents eastern Spain. The calculation is performed for a threshold of 0,01 %, which is equivalent 99,99 % system availability.

Table 6.2 shows the calculated path loss as a function of link distance (according to the above formula and conditions). The path loss is shown both with and without rain.

Table 6.2: 61 GHz calculated path-loss (PL) vs. link distance

D(km)	PL (dB) no rain	PL (dB) + rain	D(km)	PL (dB) no rain	PL (dB) + rain	D(km)	PL (dB) no rain	PL (dB) + rain
0,001	68,2	68,2	0,35	124,3	129,5	0,7	135,7	145,8
0,05	102,9	103,6	0,4	126,3	132,1	0,75	137,0	147,8
0,1	109,7	111,2	0,45	128,0	134,6	0,8	138,3	149,9
0,15	114,0	116,2	0,5	129,7	137,0	0,85	139,6	151,8
0,2	117,2	120,2	0,55	131,3	139,3	0,9	140,9	153,8
0,25	119,9	123,6	0,6	132,8	141,5	0,95	142,1	155,7
0,3	122,2	126,7	0,65	134,3	143,7	1,00	143,3	157,6

The formula for C/N at receiver is:

$$C/N = P_{TX} + G_{TX\_ANTENNA} + G_{RX\_ANTENNA} - PL + 174.5 - 10\,\mathbf{log}_{10}(BW) - NF$$

where:

C/N - carrier over noise power

P_{TX} - transmit power

$G_{TX\_ANTENNA}$ - gain of transmit antenna

$G_{RX\_ANTENNA}$ - gain of receive antenna

PL - path loss

BW - bandwidth

NF - noise factor

6.12.2.5.1 One frequency theoretical system results

In this case, the capacity is limited by the 180 m link interference with the 90 m link. Without rain, the link budget difference is 116 - 108,6 = 7,4 dB. This generates a noise floor of 7,4 dB that would limit the used modulation to about QPSK with rate 0,5. The spectral efficiency in such a case would be 2 × 2 × 0,5 × 0,7 = 1,4 bit/s/Hz. **This spectral efficiency translates to an available throughput of 5 × 1,4 = 7 Gbit/s** when using the single 5 GHz channel. We additionally apply the link budget calculation to the 90 m link, to ensure that the link budget is positive in the presence of rain.

6.12.2.5.2 Two frequencies theoretical system results

In this case, the capacity is limited by the 270 m link interference with the 90 m link. Without rain, the link budget difference is 120,9 - 108,6 = 12,3 dB. This generates a noise floor of 12,3 dB that would limit the used modulation to about QAM16 with rate 0,5. The spectral efficiency in this a case would be 2 × 4 × 0,5 × 0,7 = 2,8 bit/s/Hz. This spectral efficiency translates to an available throughput of 2,5 × 2,8 = **7 Gbit/s** when using two 2,5 GHz channels.

6.12.2.5.3 One frequency practical system results

In this case, the capacity is limited by the 180 m link interference with the 90 m link. Without rain, the link budget difference is 116 - 108,6 = 7,4 dB. This generates a noise floor of 7,4 dB that would limit the used modulation to about QPSK with rate 0,5. The spectral efficiency in such a case would be 1 × 2 × 0,5 × 0,7 = 0,7 bit/s/Hz. This spectral efficiency translates to an available **throughput of 0,25 × 0,7 = 0,175 Gbit/s when using the single 0,25 GHz channel**. We additionally apply the link budget calculation to the 90 m link, to ensure that the link budget is positive in the presence of rain.

6.12.2.6 Two frequencies practical system results

In this case, the capacity is limited by the 270 m link interference with the 90 m link. Without rain, the link budget difference is 120,9 - 108,6 = 12,3 dB. This generates a noise floor of 12,3 dB that would limit the used modulation to about QAM16 with rate 0,5 (the highest modulation we assumed possible). The spectral efficiency in this a case would be 1 × 4 × 0,5 × 0,7 = 1,4 bit/s/Hz. This spectral efficiency translates to an **available throughput of 0,25 × 1,4 = 0,35 Gbit/s when using a two 0,25 GHz channels.**

6.12.2.7 Spectral efficiency and required channel BW

As exemplified earlier, the available data rates and the spectral reuse capability at the 60 GHz frequency band are very high. The question of spectral efficiency is therefore expected to be insignificant in the majority of cases. However, there are situations in which spectral efficiency might be of interest, the prime example being administrations that require a licensing fee for use of the 60 GHz spectrum. In such situations, the interest of the operator using the backhaul system is to be as spectrally efficient as possible. To demonstrate this point, we can calculate the required channel BW in order to support the rollout scenario described previously. For this calculations we should assume that each HBS sector support 61 Mbit/s. The required channel BW for all the cases discussed is summarized in table 6.3.

Table 6.3: Minimum channel BW requirement for various 60 GHz backhaul scenarios

Scenario description	Minimum Required channel BW (MHz) to support 61 Mbit/s
Theoretical system, one frequency	1 × 43,6 MHz
Theoretical system, two frequencies	2 × 21,8 MHz
Practical system, one frequency	1 × 87,1 MHz
Practical system, two frequencies	2 × 43,6 MHz

As may be seen from the table above, the required channel bandwidths are very small comparable to the 5 GHz of spectrum available at 60 GHz.

7 Identification of Requirements

7.1 General Requirements

The general requirements include very important, but less technical aspects that should be considered during the architecture phase. First list consisting of descriptive items can be seen as a translation of user needs and expectations based on the usage scenarios.

Identified user and business needs:

- High capacity data network should cover locations with high user density.
- Network capacity should be sufficient to provide connectivity during the most busy hours of the day.
- The network should operate at vehicular speeds up to 70 km/h to include stationary and mobile users.
- The system should be transparent to the end user and should take into account the user perception, including the following factors.
- Handover.
- Power efficiency.
- Un-obstructive system antennas.
- Latency of the mobile data communication should be similar to that of a fixed broadband service.
- Communication quality should satisfy the used applications.
- Uplink and downlink rates should be at least 300 % higher than the IMT-Advanced requirements.

The second list provides criteria for the design of a solution:

- The mobile service should cover 95 % of the area capacity, including indoors and internal yards.
- Area of a multi-floor building will be considered as the number of floors multiplied by the floor area and divided by 4. It is considered that only 25 % of the indoor users will use the mobile cellular service.
- The deployment of this system deployment should use the Manhattan grid as reference model, as described in [i.1].
- The typical number of building floors in urban area should be considered seven.

7.2 Access Wireless Network

The following design characteristics have been considered as a starting point for further development of the architecture:

- ABS mounted on street poles, for example those used for illumination and for traffic signs.
- Each ABS coverage area will be calculated and evaluated for sensitivity to the following parameters:
  - Required licensed spectrum in 2,5 GHz or 3,5 GHz bands.
  - Required un-licensed spectrum.
- Target for the worst case ABS coverage: outdoor-to-indoor, shop basement floor with windows.
- 20 % to 30 % of the available ABS capacity will be reserved for in-band backhauling.
- ABS deployment cost: minimum, taking into account the ABS sector cost.

- ABS types to be used in access deployment:
    - Micro-cell (ABS on street).
    - Pico-cell (ABS for radio hole coverage, such as interior garden).
    - Femto-cell (indoor ABS).
- ABS required capacity: derived from capacity density, based on covered area.
- The architecture should be able to adapt to support UL/DL ratio of 50 % of data capacity. This requirement may need to be satisfied during limited time slots and may have an effect on the end user available DL data rates.

7.3 Self-Backhauling Wireless Network

Self-backhauling is a complex and important topic. Existing technologies used for backhaul have the tendency to be expensive or problematic due to stringent radiation regulations enforced in EU countries. With that in mind an innovative approach should be created, tested, and analysed.

The following identified technical and business requirements are pertinent to the self-backhaul wireless network:

- Should use at least 20 % of licensed spectrum.
- Preferential use of in-band (licensed spectrum) self-backhauling, to insure high QoS for the video traffic.
- Minimization of the number of Hub Base Stations and their number of sectors.
- Preferential topography should be based on LOS segments, for using the 60 GHz license-exempt spectrum;
- The number of LOS segments should be reduced, for limiting the delay introduced by Point-to-Point 60 GHz; links, deployed in a "drop-and-insert" mode.
- The system should include redundancy and should be able to sustain failure of an ABS. This robustness may be achieved by specifying alternative radio paths, and support temporary replacement of an ABS with a pico ABS.

7.4 Joint Access & Self-Backhaul

To be able to meet the capacity needs of 1 Gbit/s/km^2, a tight joint design between access and self-backhauling wireless networks is inevitable. The following technical requirements, grouped based on two possible approaches, are pertinent to such a joint design:

7.4.1 First approach

The first approach separates in frequency domain the interference between the access and self-backhaul links:

- Ensure coexistence between access and self-backhaul without jeopardizing operation/stability of individual networks.
- Suitable spectral allocation and separation between access and self-backhaul.
- Suitable power allocation and RRM algorithms to avoid capacity bottlenecks at ABSs by ensuring similar capacities in access and self-backhaul network.
- Self-backhaul design which takes both heterogeneity as well as capacity & requirement needs of access into account.

7.4.2 Second approach

The second approach is based on the following requirements:

a) the system architecture uses the same frequency band for the wireless backhaul and access links;

b) decisions are taken in a distributed fashion.

For satisfying the requirements above, is necessary that:

a) a solution in form of decisions can be found, even if only iteratively and numerically;

b) these decision yield clear instructions on radio resource management functionalities to all involved parties; and

c) these decisions are based on truly cognitive algorithms with elements of memory, learning and intelligent decision taking.

The is further requested to introduce innovative techniques which improve:

a) on the convergence speed of the cognitive algorithms; and

b) on the precision of the taken decisions versus some prior set targets.

7.5 Requirements related to the Lower Layers of DCO

The following describe the requirements for the DCO operation:

1) The system should allocate a time resource for DCO operation of one of more of ABS, HBS, HSS, MSs, etc.
2) The system should use one of the framing described above as Mode 1 or Mode 2.
3) For each communication group a time and/or frequency resource should be used either in shared or dedicated mode.
4) The cellular operation should continue using the same resource, if possible (Mode 2).
5) The system should determine what time/frequency resources can be used in parallel with DCO.
6) The system should determine if the multi-user MIMO, cooperative MIMO or Network MIMO can be used for increasing the DCO spectral efficiency.

7.6 Conclusion

The requirements presented in this summary should be treated as a guideline in the process of designing the new architecture - a guideline where some parameters have been highlighted as more important than others.

8 Business aspects

The UMTS Forum whitepaper [i.3] presents in a clear way the need for new solutions to the growing problem of 'revenue and traffic decoupling'. Therefore, every new solution should show the potential to improve the transmission parameters, in addition to the cost savings opportunities.

The following factors should be considered when performing economic evaluation.

8.1 Frequency License Fees

Operators planning to deploy a mobile data network should also obtain a license to operate at a given frequency (typically a onetime charge allowing use of the frequency in the whole country or territory) and also to pay for use of backhaul frequencies where applicable. Various techniques are being used to better utilize available frequencies. For backhaul purposes it is possible to use both licensed and unlicensed frequencies.

The frequency license fees can constitute an important economical factor of the basic deployment costs. There are two types of licensing fees:

- The corresponding part of the country-wide or region-wide license cost.
- The cost of the microwave links.

8.2 Site Related Cost

Site acquisition costs contain all activities involved with preliminary identification of a new site and with actions leading to preliminary acceptance of terms by involved parties:

- Measurements cost (CAPEX) - Once a site has been identified, a set of measurements should take place. These measurements should be performed to satisfy regulations forcing operators to comply with local laws governing the radiation exposure.
- Infrastructure building (CAPEX) - This component of the cost includes all activities performed during the site preparation, installation of equipment, and final acceptance.
- Infrastructure components cost (CAPEX) - Each location contains a set of equipment selected for a given type of site.
- Infrastructure insurance (OPEX) - Operators obtain insurance for each installation to mitigate the risk of losing expensive components of the network due to accident, theft, or weather conditions.
- Site infrastructure maintenance (OPEX) - As with any other equipment, Telco infrastructure components require regular maintenance.
- Leasing (OPEX) - Site leasing costs are market driven and may vary depending on the demand in a given area. City centres are the most expensive due to lack of good locations and continuous need for expansion of network infrastructure.

8.3 Network Equipment Cost

- Permission fee (CAPEX) - A onetime fee paid to the government body undersigning permission for utilization of the Base Station.
- Base Station (BS) costs (CAPEX) - Base station cost includes all equipment installed in a site.
- Antenna system cost (CAPEX) - Separate from other equipment antenna cost is another substantial item on the shopping list.
- Network equipment installation (CAPEX) - Network equipment installation cost includes hardware and software installation and configuration.
- Energy consumption (OPEX) - Depending on the size and power of components energy consumption could be fairly substantial. This is especially noticeable where equipment should be cooled with dedicated air conditioning system. Individual BS sites require 3 kW to 4 kW of power. We have considered in the computations below a price of 0,15 Euro per kWh.

8.4 Self-Backhaul Cost

Self-backhaul cost is associated with the communication between base stations and the base station controllers (3GPP network) or ASN GW (WiMAX network). Backhaul connectivity can be achieved with dedicated lines or with point-to-point microwave. This is also a substantial portion of the investment.

Currently fibre optics and microwave are the primary technologies used for backhaul communication. In the first case the cost involves all activities needed to lay the fibre in the ground (permissions, installation, material) and equipment cost. With microwave transmission situation is a bit simpler - line of site installation (includes components, licensing, installation, and lease); however, not without problems.

8.5 Conclusions

While CAPEX, OPEX and financial criteria cannot be addressed with technology alone, there is a need to relate architecture options to cost values for a given component. This is an identified business requirement and possibly decisive factor on a route towards new generation telecommunication solutions.

9 General Conclusions

The BWA system presented in the present document includes a number of elements enabling the feasibility of an area density capacity of at least 1 Gbit/s/km^2. Such elements are:

- The creation of a heterogeneous wireless network, composed of a hub base station and a number of access base stations.
- The hub base station is used mainly for feeding the access base stations, either in-band, by the use of a multi-beam antenna, either out-of-band, by the use of license-exempt spectrum in 5 GHz or 60 GHz.
- A multi-beam antenna, used in conjunction with collaborative MIMO techniques for improving the spectral efficiency of the in-band feeding links of the access base stations.
- Interference mitigation between the hub and access base stations, by using a number of cognitive and docitive RRM algorithms.

Furthermore, the feasibility of the target capacity of 1 Gbit/s/km^2 is demonstrated through simulations.

History

Document history		
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